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<b>14. ABSTRACT</b> Technology-Enabled Learning and Intervention Systems (TELIS) describes a development model and associated tools for advanced educational products and applications. As an extension of this roadmap, SimCenter Hawaii has developed a research design model that addresses specific challenges (e.g., improved user interfaces, the development of telecollaboration tools) directed toward improving the development of effective TELIS educational applications that can benefit the military's training programs. The following 3 medical simulation projects are herein proposed under the SimCenter Hawaii's TELIS model: 1) Implementing a combination of usability engineering methods, an evaluation model that combines two iterations of heuristic usability evaluations and one iteration of user testing, will achieve measurable software design improvements in development of the VR nephron; 2) Didactic training plus VR Triage training will result in improved triage skills acquisition over didactic training alone; and 3) the Virtual Reality Motor-Skills Simulator will result in equal or better results than a box trainer in developing fine-motor surgical skills, as assessed by performance of a virtual procedure on the LapSim simulator.					
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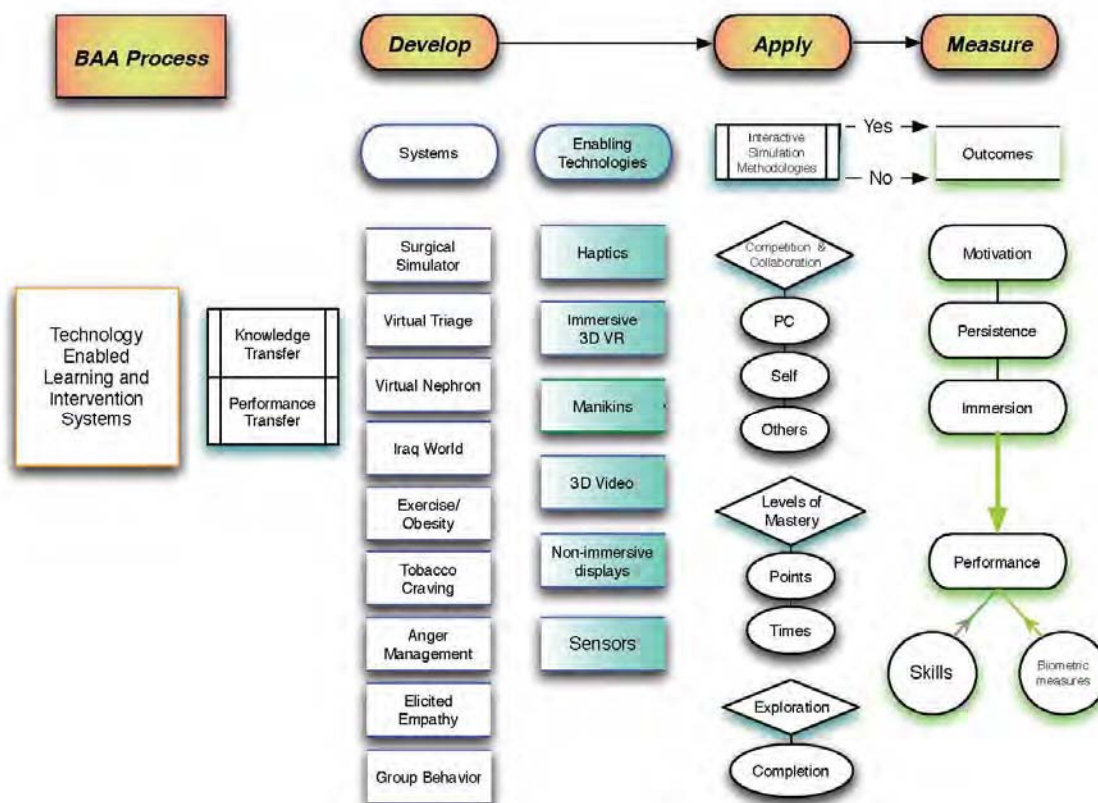
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## Introduction

Currently, technology has evolved to potentially transform learning systems, however; to achieve effective learning tools, great effort must be taken to develop, test and disseminate the technology.(3) A systematic, reproducible approach to research and development must be implemented so that results produce usable, validated, learning systems. SimCenter Hawaii's research model Technology-Enabled Learning and Intervention Systems (TELIS) (*Figure 1*) represents the overarching theme of advanced health care technologies and educational research being undertaken by our interdisciplinary research group in Hawaii. TELIS is motivated by The Learning Federation Project's technology research roadmaps, which provide an important needs assessment for current and future TELIS applications.(1-3) SimCenter Hawaii has developed a model that is based on three related action areas: development, application, and measurement.

Figure 1. SimCenter Hawaii: Research and Development Model for TELIS Applications



Despite the advantages of virtual reality (VR) medical simulations, due to cost and availability, the educational technologies used for training remain significantly underdeveloped and underutilized.(10) Simulation technology has not become part of the core curriculum at most medical schools.(8) In the federal arena as of 2005, only 14 out of 198 federal training courses on terrorism used computer/technology-based learning applications; only 6% of the training systems were VR based, and only 31% were simulation based.(15)

**SimCenter Hawaii Projects.** Projects in the SimCenter Hawaii's model may apply diverse technologies for diverse topics, but sustain the common goal of technological innovation, research, and development, in simulation technology with the desired outcome of producing and validating advanced learning systems and methodologies. The following projects are proposed under the SimCenter Hawaii's TELIS model:

- *Project 1, VR Nephron - Development:* Renal physiology contains many abstract concepts that have been identified as difficult for students to learn and understand, with the counter-current exchange system ranking number one in basic science difficulty and number two in clinical difficulty.(6) It is postulated that by visualizing and interacting with these difficult concepts, student learning will be enhanced.

This project will provide further development for the VR Nephron application — a previously developed renal physiology prototype — by adding an interactive gaming component, which allows users to navigate, explore and interact with the 3D environment. A new rules-based engine will be developed providing intelligence to the application. Graphical models and the user interface will be refined and designed to teach the counter-current mechanism in renal physiology.

After the initial prototype is complete, heuristic usability studies combined with a user evaluation will be conducted to improve software design and assess the usability of the VR Nephron application. This incremental development process permits early design modification, which saves both time and money, instead of having to redesign a system after extensive work has already been completed.(14) After prototype completion, future studies will determine whether this tool enhances the learning of renal physiology.

- *Project 2, VR Triage – Application and Measurement:* VR is a TELIS with significant potential for triage training. A 2003 study by the Federation of American Scientists concluded that the U.S. has a large, but unmet need to train first responders.(10) VR applications have theoretical advantages over paper exercises, actors, and even manikin simulations due to scenario flexibility, setup and space requirements, real-time feedback, integrated evaluation, and portability. The virtual environment can be designed to mimic battlefield or mass casualty settings, and trainees can go through the steps of triage and be tested by the computer. Although certain VR systems can provide realistic, procedural skills training,(12) the scenarios developed for triage would primarily develop and assess cognitive skill sets. As such, a VR triage curriculum would be an excellent method to develop, assess, and provide prospective training for providers like emergency medical technicians, for whom practice of basic patient stabilization procedures would be redundant. It is more important that these professionals practice their decision-making skills in a mass casualty scenario, or some other uncommon occurrence. With this in mind, the VR training platform for triage could be used for several purposes: a) initial training for those without any experience as prelude to manikin training; b) refresher training between intervals of manikin training; and c) competency assessment of higher level decision-making skills.

Overall for the Virtual Triage project, we propose that VR can be utilized in triage training for several purposes: a) initial and subsequent training (with or without previous VR training) for decision-making skills, and b) competency assessment of decision-making triage skills. Through previous funding, a VR triage application has been developed. The current proposal conducts a user study to measure educational outcomes. The intention of the project is to improve learning and performance through VR training. Students will pre-train using a web-based training module, and then conduct triage on three sequential triage

scenarios, each with five VR casualties. Self-efficacy will be assessed through questionnaires before and after the VR training.

- *Project 3, Virtual Reality Motor-Skills Trainer (VRMSS) – Application and Measurement:* With the Virtual Reality Motor-Skills Simulator (VRMSS),<sup>(5)</sup> a TELIS has been previously developed to train users on baseline fine-motor skills used in surgery in an abstract three dimensional environment. Key features include hand training for dominant and non-dominant hands, and hands working in tandem. Haptics produces force feed-back, which provides touch and feel to the application for greater realism. In order to demonstrate the learning benefit of VRMSS, this study will measure performance outcomes on a previously validated commercial simulation trainer between VRMSS and non-VRMSS trained groups.

Minimally invasive surgery has been shown to have advantages over conventional open methods. Laparoscopic procedures now represent the ‘gold standard’ for various surgical procedures. However, training is necessary to ensure a high-quality treatment of patients.<sup>(13)</sup> Surgeons are currently trained using conventional box trainers as well as high-cost virtual reality simulators. VR simulation has been validated as an effective training method for laparoscopy,<sup>(9,11)</sup> and has several advantages over box trainers including automated scoring. The Virtual Reality Motor-Skills Simulator (VRMSS), with low-cost 3D haptics input devices, is targeted for the medical student and intern level. Such a system can be implemented at the fraction of the cost of commercial counterparts. VRMSS has the special ability to run from a distributed network location, enabling distance training and improving access to this type of education.

**See Appendix D – For ppt presentation on overview of projects**

## Body

### **Task A. Project 1, Virtual Reality Nephron - Development**

This study describes the development of a multi-agent system to simulate kidney function for the purpose of teaching renal physiology to healthcare students. Renal function is modeled with particles that move within an environment, using the agent paradigm. Particles represent molecules and fluids and the environment represents the structures, membranes and volumes of the kidneys. Particles move dynamically through the system, responding appropriately depending on their surroundings. Results of heuristic and usability testing by medical students demonstrated that the 3D virtual reality educational tool developed was well accepted by users.

### **Study Design**

The studies took place at a medical school simulation center. Data for the heuristic evaluation and the individual user evaluation were collected through interviews and written surveys. The research protocols were approved by the University of Hawaii Committee on Human Studies and the United States Army Medical Materiel and Research Command Office of Research Protection.

### **Heuristic Evaluation**

Usability testing is critical to the development of an effective software application to ensure that the learner is able to focus on the educational objective rather than the process of completing tasks in the virtual environment. The heuristic usability evaluation is a systematic approach to software development that is designed to identify significant usability issues early in the software development life cycle. The heuristic evaluation of this application was modeled on the method proposed by Nielsen (1993) for software usability testing. Each new evaluator contributes progressively less new information regarding usability issues and problems. By the fifth usability tester, 85% of problems have been identified, and additional testers mostly replicate information that has already been discovered. Tang and colleagues (Tang, 2006) found that a second iteration of the heuristic methodology demonstrated additional improvement in the user interface that was being developed.

In this study, a convenience sample of medical students and one faculty member was recruited by email. Two sessions were planned separated by approximately one month of software development. Open-ended comments by the evaluators were collated and categorized as gaming or content issues.

### **Individual User Evaluation**

A convenience sample of medical students was recruited by email. Users were given a group of seven tasks to perform before completing a survey. The survey consisted of five domains, each rated on a 7-point Likert scale from 1=unacceptable to 7=exceeds expectations. An acceptable level was defined as a score  $\geq 4$ . The domains were learnability, efficiency, memorability, errors, and satisfaction. The task list for users was this:

1. Login to the virtual nephron game;

2. Orient to the environment: within the first person view, change the orientation to identify proximal, distal, cortical, and medullary perspectives;
3. Use the paddle interface to find and select the glomerulus, proximal convoluted tubule, and collecting duct.
4. Use the paddle interface to change the view from hovering view to head-up view, and from hovering view to foot view;
5. Use the paddle interface to change the functional representation of the nephron, and to activate sodium particles and urea particles;
6. Use the paddle interface to navigate to different sites of active transport (depicted in the mechanical view as moving pistons
7. Exit the virtual environment.

**See Appendix A** - Wang K, Reed N, Vincent D. (2009). *Multi-Agent Simulation of Kidney Function*. In Multi-Agent Systems for Health Care Simulation and Modeling. IGI Global (in press).

### **Task B. Project 2, Virtual Reality Triage – Application and Measurement**

Virtual reality (VR) environments offer potential advantages over traditional paper methods, manikin simulation, and live drills for mass casualty training and assessment. We measured the acquisition of triage skills by novice learners after exposing them to three sequential scenarios (A, B, and C) of five simulated patients each in a fully immersed 3D VR environment. We hypothesized that learners would improve in speed, accuracy, and self-efficacy.

**Methods.** Twenty-four medical students were taught principles of mass casualty triage using three short podcasts, followed by an immersive VR exercise in which learners donned a head mounted display and three motion tracking sensors, one for their head and one for each hand. They used a gesture-based command system to interact with multiple VR casualties. For Triage Score, one point was awarded for each correctly identified main problem, required intervention, and triage category. For Intervention Score, one point was awarded for each correct VR intervention. Before and after surveys measured self-efficacy and reaction to the training.

**Results.** Four students were excluded from analysis due to participation in a recent triage research program. Results from twenty students were analyzed. Triage Scores and Intervention Scores improved significantly during scenario B ( $p < 0.001$ ). Time to complete each scenario decreased significantly from A (8:10 minutes) to B (5:15 minutes) ( $p < 0.001$ ) and from B to C (3:58 minutes) ( $p < 0.001$ ). Self-efficacy improved significantly in the areas of prioritizing treatment, prioritizing resources, identifying high risk patients, and beliefs about learning to be an effective first responder.

Medical student year of training	No. (%)
MS1	12(60)
MS2	3(15)
MS3	3(15)
MS4	2(10)

Table 1. Medical school year of training

	VR Simulation Mean (SD)
1. The material covered was relevant to my duties as a healthcare team member.	6.5(0.61)
2. The course objectives were adequately explained.	6.3(0.97)
3. The course was well organized.	6.5(0.69)
4. The material was presented in an interesting way.	6.8(0.55)
5. The course communicated the material effectively.	6.7(0.59)
6. As the course progressed, my questions were answered.	6.8(0.44)

Table 2. Evaluation of VR triage course (7-point Likert scale: 1=strongly disagree, 4=neutral, 7=strongly agree)

	VR Simulation Mean (SD)
1. How was the pace of the course? (1=too slow, 4=just right, 7=too fast)	4.2(0.39)
2. How was the level of difficulty of the course? (1=too hard to understand, 4=just right, 7=too easy)	4.5(0.83)

Table 3. Pace and difficulty of VR triage course

	Before Mean (SD)	After Mean (SD)	p value
1. I feel confident that I will learn to be an effective first responder.	4.0(0.69)	4.2(0.62)	0.034
2. I feel confident that patients will consider me an effective first responder.	3.8(0.64)	4.1(0.60)	0.006
3. I feel confident in my ability to prioritize the treatment of patients in a mass casualty situation.	3.2(0.89)	4.2(0.52)	0.001
4. I feel confident in my ability to prioritize the use of resources in a mass casualty situation.	3.1(0.97)	4.2(0.75)	0.001
5. I feel confident in my ability to identify high risk patients for immediate treatment in a mass casualty situation.	3.4(.88)	4.2(0.77)	0.008

Table 4. Self-efficacy (5-point Likert scale: 1=never to 5=always)



Figure 1. A medical student, wearing a head mounted display and two sensor-gloves, checks the pulse of a simulated casualty in the virtual environment.



Figure 2. The same student checks a simulated casualty's carotid pulse in the virtual environment, using a virtual hand that is mapped to their right sensor-glove. The fingers of the virtual hand move up and down at the pulse rate when positioned over the carotid, radial, or femoral regions. Pulse rate and strength also appear in the left upper visual field of the head mounted display. Some students described "feeling" the pulse of the VR patient.

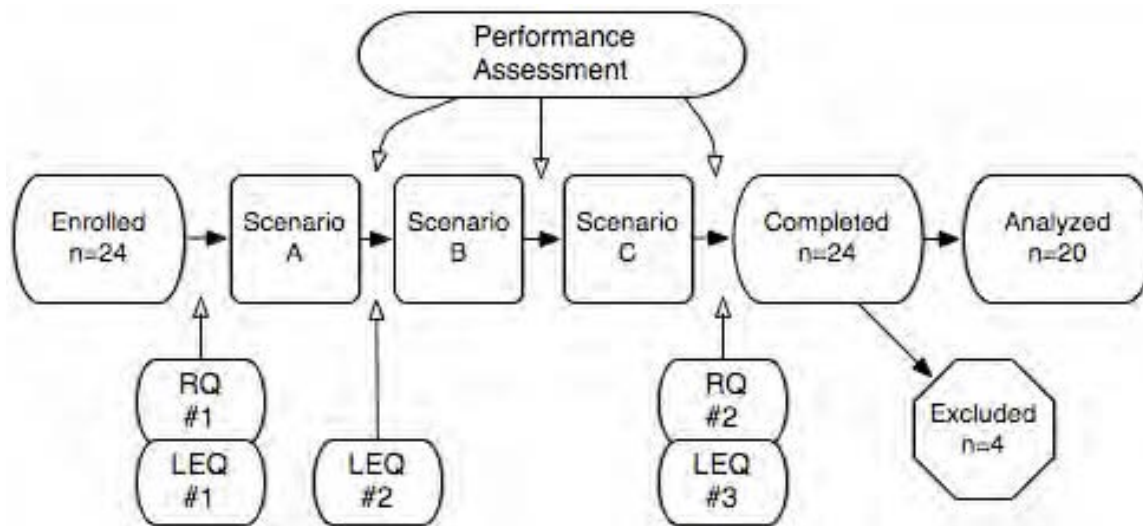


Figure 3. Study design. RQ = Reaction Questionnaire, LEQ = Learner Evaluation Questionnaire

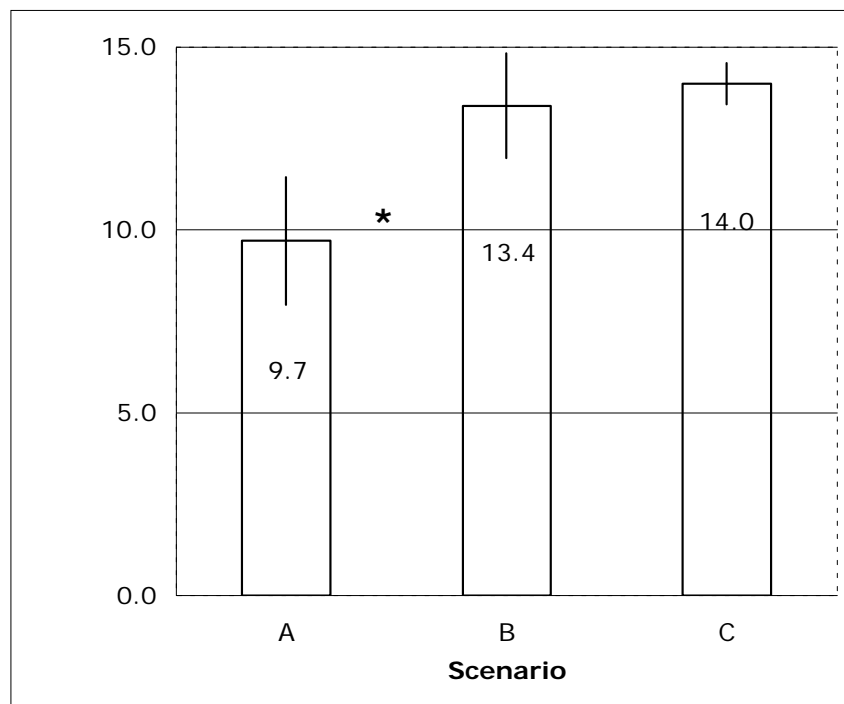


Figure 4. Average Triage Score per learner (max=15). Significant difference, \* $p < 0.001$

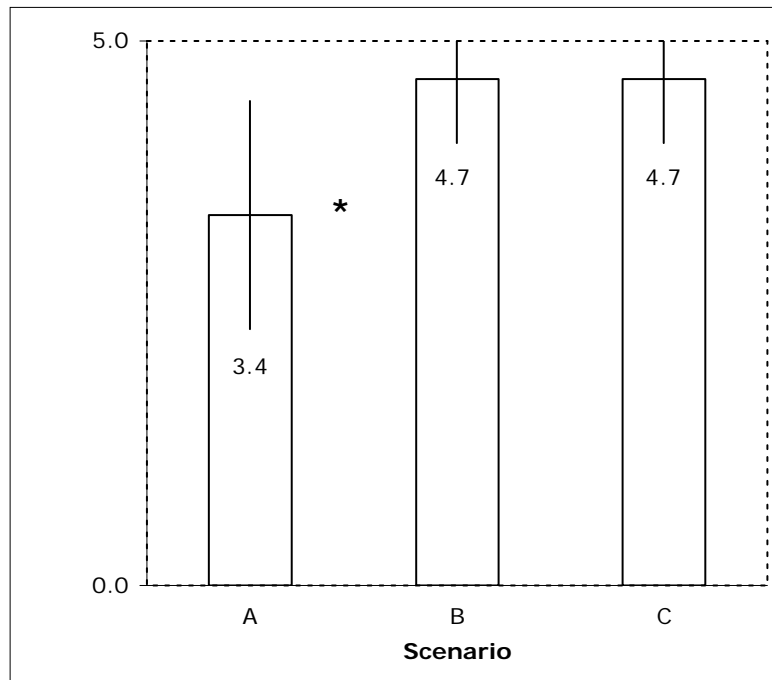


Figure 5. Average Intervention Score per learner (max=5). Significant difference, \* $p < 0.001$

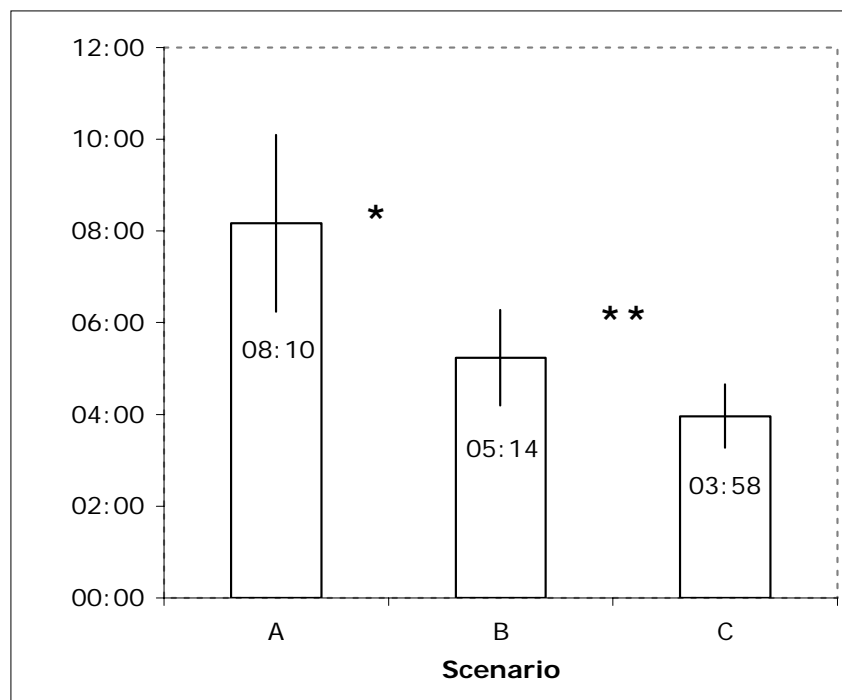


Figure 6. Time to triage one scenario consisting of five simulated patients. Significant difference, \* $p < 0.001$ , \*\* $p < 0.05$

**See Appendix B** - Vincent D, Sherstyuk A, Burgess, Connolly K. *Teaching Mass Casualty Triage Skills using Immersive Three-dimensional Virtual Reality*. Acad Emer Med 2008: 15:1-6.

### **Task C. Project 3, Virtual Reality Motor-Skills Trainer – Application and Measurement**

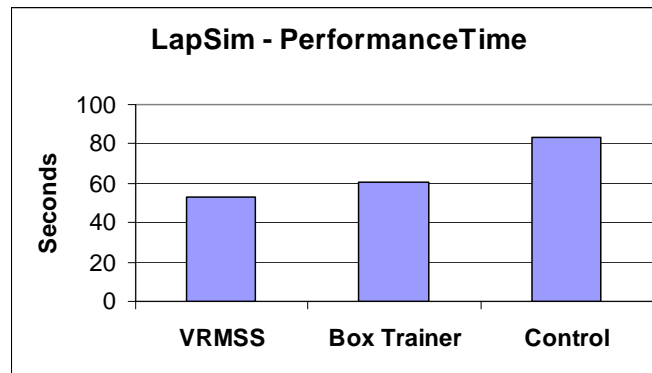
A prototype low-cost virtual-reality motor-skills simulator (VRMSS) was created using the SPRING platform as the underlying development tool at the Telehealth Research Institute, John A. Burns School of Medicine, in conjunction with the National Biocomputation Center, Stanford University. The VRMSS was specifically designed to teach baseline fine-motor skills used in surgery that are based on a matrix of elemental technical skills that comprise the tenets of surgical technique. Following initial audio/video based instruction; bead-like objects are moved to holding cups/target areas within a non-threatening abstract 3-Dimensional environment in laparoscopic, microscopic, and endoscopic formats.

### **Methods**

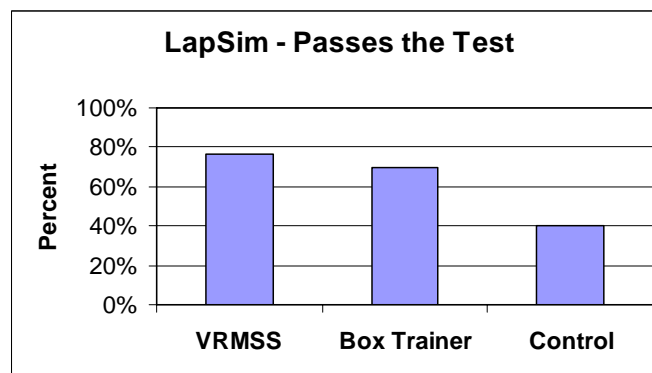
Fifty-seven participants were randomly assigned to one of three groups to conduct an evaluation study of the VRMSS. To assess fine-motor skills participants performed the basic skills of grasping, lift & grasping and coordination on the LapSim from Surgical Sciences. Each group then received time-equivalent training. The first group trained on the VRMSS. The second group trained on a box trainer used for laparoscopic training. The third, control group, read through two chapters of online curriculum on telemedicine. Participants were then reassessed on the LapSim for changes in fine-motor surgical skills.

### **Results**

The grasping and lifting & grasping tasks were not significantly difficult and all groups performed well on those tasks. Figures 4 and 5 show highlights of group performance on the LapSim coordination task after training. Group performance times in Figure 4 show a significant difference between the groups (mean = 66.3 seconds,  $F=3.423$ ,  $p<0.04$ ). The post hoc test (Tukey) showed that VRMSS and the box trainer mean completion times were not significantly different and the control group had a significantly longer performance time ( $p<0.044$ ). Figure 5 shows the pass percentage for the groups. The VRMSS and box trainer groups were very similar and both training were at least 1.75 times better than the control group.



**Figure 1.** Shown is the mean time of each group on the coordination task after receiving training



**Figure 2.** Shown is the percent of participants from each group that passed the LapSim on the coordination task after receiving training.

**See Appendix C -** Ikehara C, Aschwanden C, Burgess L, Montgomery K, Mok D. (2009). *Evaluating a Virtual Reality Motor-Skills Simulator. MMVR 2009.*

## **Key Research Accomplishments**

### *Task A. Project 1, Virtual Reality Nephron - Development*

- Task A1.* Develop interactive gaming virtual reality nephron application - A user interface was created for selecting and deselecting key features of the model, enabling user defined educational exploration to take place.
- Task A2.* Complete all appropriate procedures with institutional review boards – Protocol has been approved by USAMRMC ORP HRPO for exempt status (in addition to UH IRB). All appropriate procedures with institutional review boards have been completed.
- Task A3.* Conduct heuristic usability study and present/draft results - see appendix A

### *Task B. Project 2, Virtual Reality Triage – Application and Measurement*

- Task B1.* Complete all appropriate procedures with institutional review boards – Protocol has been approved by USAMRMC ORP HRPO for exempt status (in addition to UH IRB). All appropriate procedures with institutional review boards have been completed.
- Task B2.* Conduct acquisition of triage skills study – 24 participants successfully completed the study.
- Task B3.* Skills acquisition relative to self-efficacy study – results showed that self-efficacy improved significantly in the areas of prioritizing treatment, prioritizing resources, identifying high risk patients, and beliefs about learning to be an effective first responder.
- Task B4.* Analyze data, interpret results and draft manuscript for publication – see Appendix B

### *Task C. Project 3, Virtual Reality Motor-Skills Trainer – Application and Measurement*

- Task C1.* Complete development of VRMSS trainer – VRMSS software and scenarios were developed and tested.
- Task C2.* Complete all appropriate procedures with institutional review boards; prepare flyers for participant recruitment; setup equipment and tasks – Protocol has been approved by USAMRMC ORP HRPO for exempt status (in addition to UH IRB). All appropriate procedures with institutional review boards have been completed.
- Task C3.* Conduct acquisition of surgical skills study - 60 participants have undergone the surgical skills study. Data including performance measures and questionnaires has been collected from all 60 participants.
- Task C4.* Analyze data, interpret results, and draft manuscript for publication, and update web site – see Appendix C

### Reportable Outcomes

- **Publication** – Wang K, Reed N, Vincent D. (2009). *Multi-Agent Simulation of Kidney Function*. In Multi-Agent Systems for Health Care Simulation and Modeling. IGI Global. (Appendix A)
- **Publication** – Vincent D, Sherstyuk A, Burgess, Connolly K. *Teaching Mass Casualty Triage Skills using Immersive Three-dimensional Virtual Reality*. Acad Emer Med 2008: 15:1-6.
- **Publication** – Ikehara C, Aschwanden C, Burgess L, Montgomery K, Mok D. (2009). *Evaluating a Virtual Reality Motor-Skills Simulator*. MMVR 2009 (Appendix C)

## Conclusions

Simulator-based training has been shown to improve outcomes for both cognitive as well as motor-skills training.(7) Cognitive modules can be distributed through advanced learning networks.(4) This has significant implications, because enterprise wide educational solutions can be developed at one center and accessed by the entire enterprise remotely. The Army Knowledge Network is an example of such a solution, and sophisticated training modules being developed at SimCenterHawaii can be placed centrally and accessed remotely. In addition to the learning networks, experiential training with virtual reality can better meet training objectives by simulating the “real patient.” A distributed curriculum, which can provide greater accessibility to didactic learning materials, coupled with a hands-on VR-based and virtual reality training curriculum can provide a multidisciplinary training program to enhance the training of first responders.

Our research within this proposal strives to further develop and demonstrate that simulation training with virtual reality software and/or manikins can not only better meet training objectives than with a didactic curriculum alone, but provide a hands-on alternative to moulage field exercises in a less expensive and more readily available platform. Both manikin-based and virtual reality training curriculums can be integrated into a multidisciplinary training program to enhance the training of first responders.

Through this proposal, we have conducted the following studies:

- *Heuristic Usability Evaluations* - The software development and evaluation model that we have developed consists of two iterations of expert heuristic testing and one evaluation using typical users of the system. As key to the success of VR Nephron, it is vitally important that the application is usable and able to satisfy the needs of the training, without hindrance of the technology itself. Therefore, in the development process of VR Nephron, we have developed and utilized a heuristic usability evaluation model.

*Conclusion* - We believe that simulations will provide an increasingly realistic and effective method of teaching concepts to medical/healthcare students. Human physiology is very complex, and still not completely understood. Creating models and performing simulations has the potential to help us gain a more complete understanding of how the body works, and ultimately improve patient care.

The modeling of the physiologic variables, as well as the addition of stylistic components of gaming motifs, remains a work in progress. Based on feedback from the students, the current version of the nephron game is probably most suitable for novice learners of renal physiology. Although users felt that the interface was easy to learn, the present software is probably optimally used with a knowledgeable technical facilitator present. The development of the virtual reality application for use in front of a large 3D screen would make the system amenable to greater integration into a problem-based learning curriculum that emphasizes small group interaction and formative assessment facilitated by a faculty member.

Future studies would be valuable to assess the contribution of gaming elements to student learning and satisfaction, as well as to compare the impact of immersion in this virtual system to traditional non-immersive forms of education.

- *Manikin Triage Training* –This research study that will help us understand the optimal conduct of triage training using manikin simulators, and that packaging and disseminating sophisticated manikin-based online curricula can used as a more readily available and less expensive alternative to mass casualty triage training.

*Conclusion* - Novice learners demonstrated improved Triage and Intervention Scores, speed, and self-efficacy during an iterative, fully immersed VR triage experience.

- *VRMSS* – The VRMSS system has the potential to facilitate an inexpensive alternative to the current traditional methods of training, and provides a means to train laparoscopic motor skills which will improve patient safety for military personnel. Expensive desktop models are valuable, but due to their high cost, the value of simulation training is experienced by relatively few surgeons. Once this baseline application is validated locally, a distributed server-based model using inexpensive tools would help to improve access to this type of training.

*Conclusion* - With the VRMSS and box trainer groups having similar results on the LapSim assessment, it is likely that VRMSS would also have a positive impact on outcomes at surgery. However, like LapSim, VRMSS has significant advantages over the box trainer, in that the VRMSS can provide scoring on several parameters without the need of an instructor during student skill acquisition. Parameters of importance scored by the VRMSS include: time to complete task, number of errors and economy of movements. Also, the VRMSS is approximately 1/16th the cost of the LapSim.

The SimCenter TELIS model is designed to ultimately facilitate a smooth development and integration of simulation technology into education and training. Our design model provides an accepted methodology for development and validation of innovative technological learning systems. The goal of the model is to produce validated TELIS to enhance learning with all the encumbrances worked out through user testing and validation studies. In addition to the systematic approach to development, SimCenter Hawaii is proposing a broad portfolio of research that can contribute to greater educational outcomes in healthcare.

SimCenter Hawaii is motivated by the Research & Development Roadmap published by the Learning Federation,(3) which is a partnership between industry, academia and private foundations. In essence, SimCenter Hawaii's aim is to promote and identify research and development that can directly lead to improved learning outcomes and greater access to quality education and training in healthcare while promoting collaboration between different entities.

Ultimately, SimCenter Hawaii's goals for the development of TELIS are not only to foster a proven research and design methodology, but to also cultivate innovative and collaborative research and development, and to seed further growth and development in the Hawaii Pacific region. We hope not only to play a pivotal role in research and development methodology, but also to generate partnerships with private companies, universities government agencies, private

foundations and the educational community. Through our research and design model for TELIS, we can provide a platform for scientists, clinicians, engineers, industry and government to nurture and develop innovative research and solutions in healthcare.

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## Appendices

**Appendix A. *Publication*** – Wang K, Reed N, Vincent D. (2009). *Multi-Agent Simulation of Kidney Function*. In Multi-Agent Systems for Health Care Simulation and Modeling. IGI Global.

**Appendix B. *Publication*** – Vincent D, Sherstyuk A, Burgess, Connolly K. (2008). *Teaching Mass Casualty Triage Using Immersive Three-dimensional Virtual Reality*. Acad Emer Med 2008; 15:1-6

**Appendix C. *Publication*** – Ikehara C, Aschwanden C, Burgess L, Montgomery K, Mok D. (2009). *Evaluating a Virtual Reality Motor-Skills Simulator*. MMVR 2009

**Appendix D. *Presentation*** - Overview of Projects

# A Multi-Agent Simulation of Kidney Function for Medical Education

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## ABSTRACT

This chapter describes a multi-agent system to simulate kidney function for the purpose of teaching renal physiology to healthcare students. Renal function is modeled with particles that move within an environment, using the agent paradigm. Particles represent molecules and fluids and the environment represents the structures, membranes and volumes of the kidneys. Particles move dynamically through the system, responding appropriately depending on their surroundings. We describe the use of the simulation in research and teaching medical students about the renal system. Initial results of heuristic and usability testing by medical students demonstrated that the 3D virtual reality educational tool developed improves the visualization of the renal system by medical students, and student self-confidence in learning renal physiology.

## KEYWORDS

multi-agent system, kidney, medical education, nephron, particle system, renal system, simulation.

## INTRODUCTION

Renal physiology is exceptionally difficult to learn. The countercurrent exchange system of the kidney was ranked number one in basic science difficulty and number two in clinical difficulty in a 1990 survey of medical educators (Dawson-Saunders, 1990). Project TOUCH was a multiyear collaboration between the University of Hawaii and the University of New Mexico in which virtual reality (VR) applications were developed to advance medical education. One application was a 3D VR fly-through model of the kidney (Alverson & Saiki, 2006). The simulation prototype has subsequently been enhanced with a new user interface and gaming motifs. The new system underwent heuristic and usability tests that are described in this chapter.

The kidney's function is to eliminate water soluble wastes from the body (Banasik, 2000). We chose a particle system implementation because that produces a better, more detailed simulation. A multi-agent system represents the motion of molecules and the functions of the tubules in a kidney. The particles follow the tubule path dynamically using intelligent movements to simulate different kidney function, such as reabsorption and secretion.

The rest of this paper is organized as follows. First, multiagent systems and the renal system are described. Second, we describe the implementation and characteristics of our simulation system. Then the visualization of difficult concepts to aid understanding is describes. Finally, the usability experiments conducted and the results obtained are described followed by future trends for agents in medical simulations and the conclusion.

## BACKGROUND

### Multi-Agent Systems

A multi-agent system (MAS) is composed of agents, each of which selects its own course of action based upon its goals (Weiss, 1999, Wooldridge, 2002). Most definitions of agents include the following characteristics: a) An agent perceives its environment, decides on actions, and uses its effectors to perform the selected actions. b) An agent is active over a period of time, making actions based on the world it senses at the current time, c) An agent has goal(s) as well as some latitude as to how to achieve those goals (Barber et al. 2003). A multi-agent system may be incorporated in a physical (robotic) body, or sense and act upon the world entirely in software simulations, or computer applications (softbots).

Multiagent systems have been used in a broad range of applications including soccer games (Robocup, 2008), search and rescue operations (Robocup Rescue, 2008), space (Bernard et al., 1999, NASA 2008), and military applications (Zafar, 2006), including training combat pilots, troops in battlefield scenarios, and numerous training situations. Agents have been used in medical applications as well. The journal *Artificial Intelligence in Medicine* recently published a special issue on software agents in health care (Moreno & Garbay, 2005). Experience with agent systems in the GruSMA research group is described by Moreno, Valls, Isern, & Sanchez (2006).

Examples of agents in medicine include Hudson & Cohen (2006), who use agents to support rural healthcare of the elderly. Pouloupoulos, et al. (2001) use intelligent agents to track patient information in large databases for use in a telemedicine system. Prado et al. (2001) describe a telemedicine system to support patients with end stage renal disease. This system focuses on the monitoring and treatment/therapy for patients with advanced renal disease.

Most agent applications in medicine are focused on decision-support for physicians and/or patients. In contrast, the goal of our system is to teach physiological concepts to health care professionals,. When health care workers have a better understanding of the physiology of the human body, they can also understand the effects of disease processes in patients, which can improve the quality of care delivered to the patient. Our program encourages the user to experiment by changing parameters and viewing the results in simulation.

Why use agents for this project? There are many ways to represent moving molecules, which form the base for a renal simulation. Reeves (1983) introduced a particle system method for modeling fuzzy objects such as fire, clouds, and water. The resulting model is able to represent motion, changes of form, and dynamics, but this approach does not produce the randomness needed in the kidney domain.

Chenney (2004) used flow tiles for representing and designing velocity fields. Each flow tile contains small fields, and many tiles can be combined to produce a larger flow. He describes three applications: a crowd on a city street, a river flowing between banks, and swirling fog. We can apply the flow tile concept to the particle, but the problem is that flow tiles use a pre-defined path, so it is hard to use flow tiles to do reabsorption and secretion that are necessary in the kidney system.

One type of multiagent system algorithm is swarm intelligence. Baumgartner (2004) proposed particle swarm optimization which imitates the social behavior of birds in a flock flying around and sitting down on a pylon. Yoon (2005) describes a tool to generate way finding aids in dynamic virtual worlds in an ant

colony. Ants look for food by wandering randomly from their home colony. If they find food, they return to their colony while laying down pheromone (scent) trails that can be followed by other ants. The pheromones are a simple but effective means of communication. Ants are behaviorally unsophisticated and yet, collectively, they perform complex tasks. The ant colony algorithm can be run continuously and adapt to changes in real time. In another example, Schmickl (2005) modeled honey bees to forage for nectar in a fluctuating environment. Without any global decision making, the bees are able to select optimal paths, those offering the best ratio of gain to cost to and from multiple available nectar sources.

The swarm intelligence models have an advantage over simulated annealing and genetic algorithm approaches when the environment may change dynamically (Janson, 2008). They are computationally expensive, which could prevent the simulation from running in “real time”.

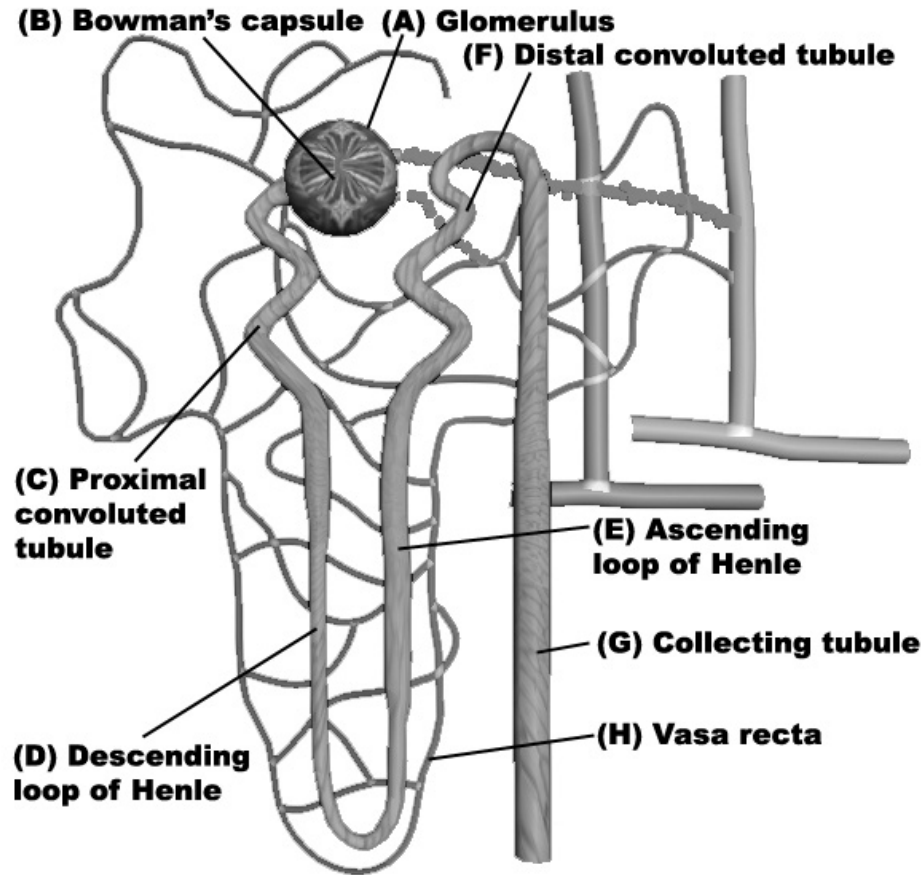
Using the ant colony analogy, the particles in our system are the ants (agents) with simple behavior rules. Their behavior produces the movement of the particles and fluids in our simulation. Even though the actions of the particles individually are simple, the result is a complex system. The agent paradigm provides a distributed framework for robustness and efficiency. The graphics engine displays the environment and the movement of the particles in 3D.

## **The structure and function of the kidneys**

Humans have two kidneys that each contains more than a million nephrons. A nephron contains eight functional parts as shown in Figure 1: (A) glomerulus, (B) Bowman’s capsule, (C) proximal convoluted tubule, (D) descending loop of Henle, (E) ascending loop of Henle, (F) distal convoluted tubule, (G) the collecting tubule, and (H) vasa recta. Thus, fluid flows from A – G in the figure. The parts and functions of the kidneys are described next.

Blood from the body enters nephrons in the kidney from the renal artery. Urea is a waste product of metabolism and is carried by the blood to the kidneys. The movement of urea is responsive to the hormone aldosterone. The kidneys are responsible for removing waste products from the blood, however when removing the wastes, electrolytes and water are also removed, and thus must be recovered. The process occurs in the following five steps.

The concentration of urine permits animals to survive on much less water than they would otherwise need to get rid of metabolic waste products. This process is unique to mammals.



*Figure 1: The eight parts of a nephron in a kidney. (A) glomerulus, (B) Bowman's capsule, (C) proximal convoluted tubule, (D) descending loop of Henle, (E) ascending loop of Henle, (F) distal convoluted tubule, (G) the collecting tubule, and (H) vasa recta (blood vessels).*

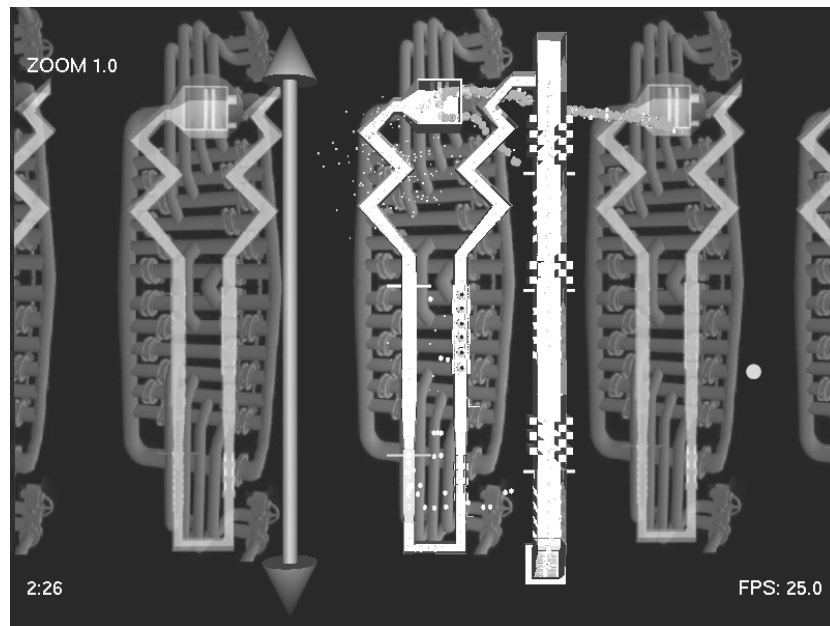
First, the glomerulus (A in Figure 1) filters fluid (plasma) from the blood into Bowman's capsule (B) while preventing the passage of blood cells and proteins from the blood. Second, the proximal convoluted tubule (C) reabsorbs two thirds of the filtered water and electrolytes and all of the filtered bicarbonate, glucose, amino acids, and vitamins. Third, the descending loop of Henle (D) reabsorbs more water and delivers a concentrated filtrate to the ascending loop of Henle (E). Fourth, the ascending loop of Henle actively reabsorbs sodium ions to produce a concentrated filtrate. Fifth, the distal convoluted tubule (F) reabsorbs additional sodium ions, chlorine ions, and water. Finally, the collecting tubule (G) reabsorbs water under the influence of antidiuretic hormone, and secretes hydrogen ions and potassium ions.

Thomas et al. (2006) provide a summary of the contributions of mathematical models of the kidney. The models are at various levels of detail and their purpose is to obtain a comprehensive understanding of renal function. To that end, the authors are creating new resources (given the name Physiome) to provide general access to current and future models to enhance collaboration between researchers.

## DESIGN AND IMPLEMENTATION OF THE MULTI-AGENT SYSTEM

This research was initially funded by Telehealth Outreach for Unified Community Health (TOUCH) (Alverson & Saiki, 2008) and implemented in the software development environment called Flatland (Flatland, 2008). The aim of Project TOUCH was to help develop a virtual reality simulation for medical education (Alverson & Saiki, 2005).

This chapter describes further work on the system including the addition of gaming motifs, as well as heuristic and usability testing. This work was supported under a grant to the University of Hawaii Telehealth Research Institute by the U.S. Army's Telemedicine and Advanced Technology Research Center (TATRC) to develop virtual reality applications.



*Figure 2: A screenshot of our simulation, showing the structure of nephrons and molecules in the kidney. The small dots show the location of particles within the kidney.*

Figure 2 shows user's simulation view of three nephrons. Each nephron is a multi-agent system consisting of an environment and agents (e.g. particles). Kidney processes are displayed when the molecules move within the environment. This uses one of the plugins in Flatland (Flatland, 2008; Alverson & Saiki, 2006). The system is written in the C programming language with OpenGL.

Each particle in the system is an agent. The agent's sensors obtain the particle's current location in its environment. Each agent/particle decides the direction and velocity it will move (if any) during the step in the simulation. Particles thus move through the environment modeling the physiological processes.

Our system is analogous to trains within a railroad system. The train system has stations and tracks in its environment, cars and passengers can be in trains or in stations, and passenger traffic represents the flow of molecules within the system.

## The Environment: Nodes and Edges

A node is analogous to a train station, while an edge is analogous to tracks. Agents move from node to node along the edges. The agents can only move where an edge exists. Each node has a 3D plane perpendicular to the edge attached to the previous node. The dot product of the particle coordinate and the 3D plane normal vector determine whether a particle passes through the node or not.

## Agents: Particles and Drams

There are two types of agents: particles and drams. Particles model either molecules including water, sodium, urea, and potassium, or fluid, including blood, plasma, water and filtrates. A particle has the following attributes: an identifier, type, location, velocity and direction. We group particles into drams to simplify the simulation since groups of agents of multiple types move through the system together. Particles can enter or exit a dram or other structure during the simulation.

A dram is a group of particles and/or fluids, representing a volume of liquid. Drams have attributes including an identifier, their current location within the environment, their current direction of motion, and their current speed. Drams move through the environment over time. Their motion represents the flow of liquid through the renal system. The ratio of reabsorption and secretion of molecules and fluids is based on characteristics of the molecule and environment. By using the dot product, a group of particles or drams can act like an agent to perceive the node and edge for actions such as reabsorption or secretion.

The particle pool is used for showing the reabsorption and secretion functions in the kidney. There are two kinds of particle pools: a temporary pool to simulate reabsorption, and a stay pool to simulate secretion. The temporary pool is used when the particle moves from inside the tubule (lumen) to outside the tubule (interstitium); the particle disappears to show movement into the interstitium for reabsorption. The stay pool uses a preexisting particle from outside the tubule (interstitium) to move to inside the tubule (lumen); the particle then joins the flow inside the tubule to simulate the secretion.

## Processes: Flow

The flow of agents in the system is produced by six operations: *enter*, *update*, *separate*, *reabsorb*, *secrete*, and *transfer*. A group of particles can *enter* to a dram and form a flow inside the tubule. As particles move through the tubule, they can move in different directions; separate a dram into two different drams; *reabsorb* from a dram to a pool; *secrete* from a pool into a dram; or *transfer* to other parts of the nephron. The particles and drams update their current positions at each step in the simulation. The transfer operation is used to show the urea gradient in the loop of Henle. The urea in the collecting tubule can flow back to the loop of Henle by moving the urea particle to a gradient pool. The gradient pool is a stay pool that demonstrates how a urea gradient can form in the kidney.

## KIDNEY FUNCTIONS

### Filtration

The filtration process occurs when small, usually uncharged, molecules move from the blood in glomerular capillaries to the Bowman's capsule. Other blood components such as red or white blood cells remain in the blood and exit the nephron without going through the tubules. The plasma and particles

recovered in the tubules are added to blood that bypasses the filtration process. The filtrate contains WUSP, which stands for molecules of water, urea, sodium, and potassium (blood plasma).

There are two paths out of the glomerulus (A), one path to the Bowman's capsule (B), and the other to the vasa recta (H). In the glomerulus node, agents sense the information about their environment, and choose one of the available paths. Then, the dram is split into two drams with filtered blood in one dram and WUSP in the other dram. In this way, blood goes directly to the vasa recta (H) where it returns to the body and is combined with recovered particles (WUSP).

## **Reabsorption**

The WUSP particles actively or passively leave the tubule, such as proximal tubule (C), descending loop of Henle (D), and ascending loop of Henle (E), reenter the plasma in the process called reabsorption. In the reabsorption node, a dram leaves the tubule its current status is obtained and it is absorbed (disappears). Next the particles move from the dram into a particle pool, and are reabsorbed.

## **Secretion**

The potassium particles move from the plasma into the collecting tubule (G), primarily by active transport. In active transport, energy is expended in the cells to force molecules through a barrier. Passive transport (diffusion) also occurs. This maintains homeostasis (pH and other properties of the blood to normal values) and rid the body of metabolic by-products and toxins. In the simulation, pre-defined particle pools are available. When needed, the particles move into the tubule.

## **Excretion**

The particles remaining in the distal tubule (F) after passing through the collecting tubule (G) leave the body as urine, the process called excretion. Excretion is modeled by particles going through the collecting tubule to the bladder. In the bladder, the dram dissolves in the flow and all particles inside are deleted.

## **Countercurrent mechanism**

A countercurrent exchange occurs when fluid currents flow opposite of each other and a property (such as concentration of a substance) is exchanged. There are several countercurrent flows demonstrated in the simulation. The descending loop of Henle (D) and ascending loop of Henle (E) are adjacent structures, and particles flow in opposite directions and are exchanged. Other countercurrent exchanges occur between the ascending loop of Henle (E) and collecting tubule (G) in the simulation. Adjacent structures that also have countercurrent flows, such as the descending loop of Henle (D) and vasa recta (H), and ascending loop of Henle (E) and vasa recta (H), are depicted in a static fashion in the model. The movement of particles in the simulation gives users a dynamic way to visualize this difficult physiologic concept.

# **VISUALIZATION SYSTEM TOOLS**

## **Menu**

The user's menu is shown in Figure 3. Parameters are easy to control using a paddle, and changes can be made during the simulation. The paddle interface is a fan with an attached inertia cube (InterSense, 2008) to detect the rotation and move the laser pointer in order to select the items as shown as a small circular

dot in Figures 2 and 3. The student is holding the paddle in Figure 4. In the menu, the user has the ability to select which particles to show in the simulation (such as water, urea, sodium, potassium, or/and blood). The user can also select whether to start or stop the flow of particles. The gaming mode allows the user to explore, question, walkthrough, or jump to different sequence. The explore mode can highlight and display the different parts of nephron game. The question mode presents a question to a user, and allows the user to select the correct part of the nephron with the paddle. The walkthrough mode runs a pre-defined path, enabling the user to view the different parts of nephron from a different camera angle. In the sequence mode, a user is able to jump to 15 different locations directly, and switch between a mechanical view and an organic view of the nephron. The mechanical view can give medical students a visual representation of the function of the nephron. The organic view shows a biological representation of the nephron.

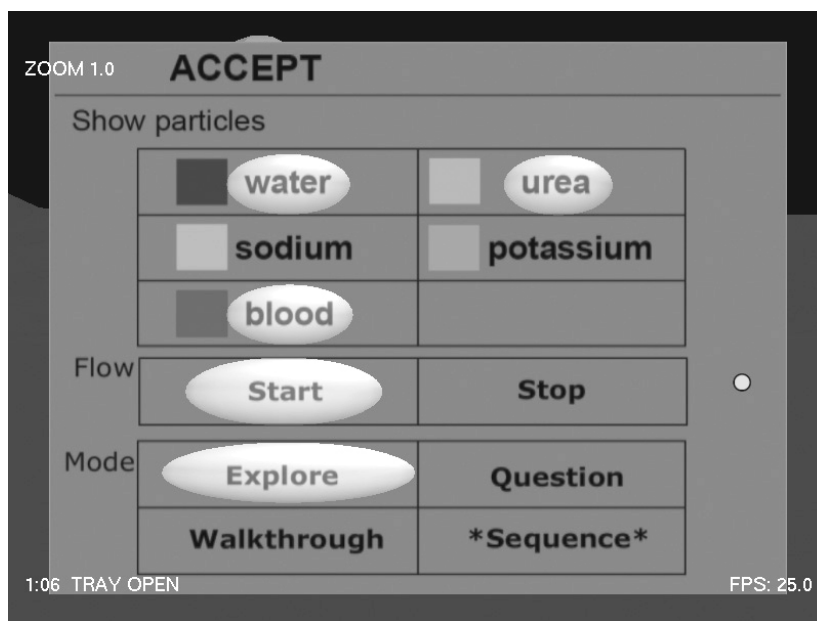


Figure 3: The menu enables the user to choose which particles to display, as well as control other parameters during a simulation.

## VISUALIZATION OF DIFFICULT CONCEPTS

### Filtration in Bowman's capsule

Small particles are filtered from the blood into a tubule in the kidneys via a semi-permeable membrane in Bowman's capsule (B in Figure 1). This is visualized by showing the particles of Urea, Sodium and Potassium along with water moving out of the blood coming into the kidneys and into a tubule. Most of the blood, containing large cells and proteins, continues to flow through the small vessels in the nephron and eventually leaves the kidneys.

Initially the size of the particles was proportional to their actual size. Urea is the largest and sodium is the smallest. Users mentioned that they could not see the Na<sup>+</sup> particles, so their size was increased.

## **Reabsorption of water and electrolytes**

The reabsorption of water and electrolytes is visualized when the particles rejoin the blood after passing through the kidneys. The particles “disappear” into the blood.

## **Counter-current exchange and multiplication**

The structures in the tubules generate a gradient where the concentration of particles increases (increasing osmolality). This occurs in the loop of Henle, in an elegant manner using the opposite direction fluid flows in the adjacent parts of the tubule to concentrate the urine. It is somewhat like a heat exchanger, which looks much like an automobile radiator, on an air vent in a building. The intake and outflow tubes are next to each other. In cold climates, the incoming cold air is warmed by the warm air going out. At the same time, the air that was warm in the building is cooled before it exits. Thus, heat is retained in the building rather than expelled with the air when bringing fresh air into the building. Without adjacent inflow and outflow, the heat would be lost with the air as it is expelled.

This is one of the key concepts to understand about the renal system. Our simulation does not visually represent the gradients in the kidneys. We would like to include this in future versions of the system. A change in color intensity could represent different levels of particles at the different parts of the gradient.

## **USABILITY STUDIES**

### **Study Design**

The studies took place at a medical school simulation center. Data for the group user evaluation were collected anonymously using an audience response polling system. Data for the heuristic evaluation and the individual user evaluation were collected through interviews and written surveys. The research protocols were approved by the University of Hawaii Committee on Human Studies and the United States Army Medical Materiel and Research Command Office of Research Protection.

### **Group User Evaluation**

First year medical students viewed the virtual reality nephron during planned laboratory sessions that were a part of their problem-based learning curriculum. All participants donned active 3D glasses, and a single student used a paddle interface to navigate the scene as it was projected on a rear mounted 3D projector. One or two faculty members mediated each 45-minute session. Students were surveyed before and after the session using an audience response system that collected anonymous, paired responses. Responses were rated using a 5-point Likert scale, from 1 = *strongly disagree* to 5 = *strongly agree* to the following statements:

- 1) “I feel confident in my understanding of nephron physiology”;
- 2) I have a good mental image of renal physiology”; and
- 3) “Renal physiology is hard to visualize.”

Observations and comments made during the group session were collated and organized into action items for the software programmers. The programmers subsequently added gaming motifs, on-screen navigation controls, a simple scoring system, as well as enhancements in the visualization of selected particles.

## **Heuristic Evaluation**

Usability testing is critical to the development of an effective software application to ensure that the learner is able to focus on the educational objective rather than the process of completing tasks in the virtual environment. The heuristic usability evaluation is a systematic approach to software development that is designed to identify significant usability issues early in the software development life cycle. The heuristic evaluation of this application was modeled on the method proposed by Nielsen (1993) for software usability testing. Each new evaluator contributes progressively less new information regarding usability issues and problems. By the fifth usability tester, 85% of problems have been identified, and additional testers mostly replicate information that has already been discovered. Tang and colleagues (Tang, 2006) found that a second iteration of the heuristic methodology demonstrated additional improvement in the user interface that was being developed.

In this study, a convenience sample of medical students and one faculty member was recruited by email. Two sessions were planned separated by approximately one month of software development. Open-ended comments by the evaluators were collated and categorized as gaming or content issues.

## **Individual User Evaluation**

A convenience sample of medical students was recruited by email. Users were given a group of seven tasks to perform before completing a survey. The survey consisted of five domains, each rated on a 7-point Likert scale from 1=unacceptable to 7=exceeds expectations. An acceptable level was defined as a score  $\geq 4$ . The domains were learnability, efficiency, memorability, errors, and satisfaction. The task list for users was this:

1. Login to the virtual nephron game;
2. Orient to the environment: within the first person view, change the orientation to identify proximal, distal, cortical, and medullary perspectives;
3. Use the paddle interface to find and select the glomerulus, proximal convoluted tubule, and collecting duct.
4. Use the paddle interface to change the view from hovering view to head-up view, and from hovering view to foot view;
5. Use the paddle interface to change the functional representation of the nephron, and to activate sodium particles and urea particles;
6. Use the paddle interface to navigate to different sites of active transport (depicted in the mechanical view as moving pistons);
7. Exit the virtual environment.



*Figure 4: A problem-based learning session using the nephron simulation and a 3D rear-mounted projector. A single medical student controls the simulation using a handheld device. The session was mediated by a faculty member.*

## Data Analysis

Before and after survey data were analyzed using a paired, t-tailed Student's t-test. Descriptive statistics are presented next.

## RESULTS

### Group User Evaluation

Sixty-one students (98% of the class) participated in six sessions with the system. Eighteen percent frequently used videogames, and 16% frequently used a Nintendo Wii. Seventy-two percent stated that they had used 3D glasses in a movie theater, but only 32% had used an educational game in medical school.

The motion-tracking interface using the head mounted tracker with a hand-held, paddle-mounted tracker proved to be problematic for members of the audience who were also watching the projected images. Observers became disoriented while the device was being used; this problem was resolved by eliminating the head-mounted motion tracker.

Students reported that some of the particles that were modeled were difficult to see. Modeling of particle dynamics in the proximal convoluted tubule was incomplete and subject to misinterpretation. Other content and usability issues were recorded and provided to software programmers for further

development. For example, one task was to increase the size of the white particles (simulating sodium ions) to make them more visible.

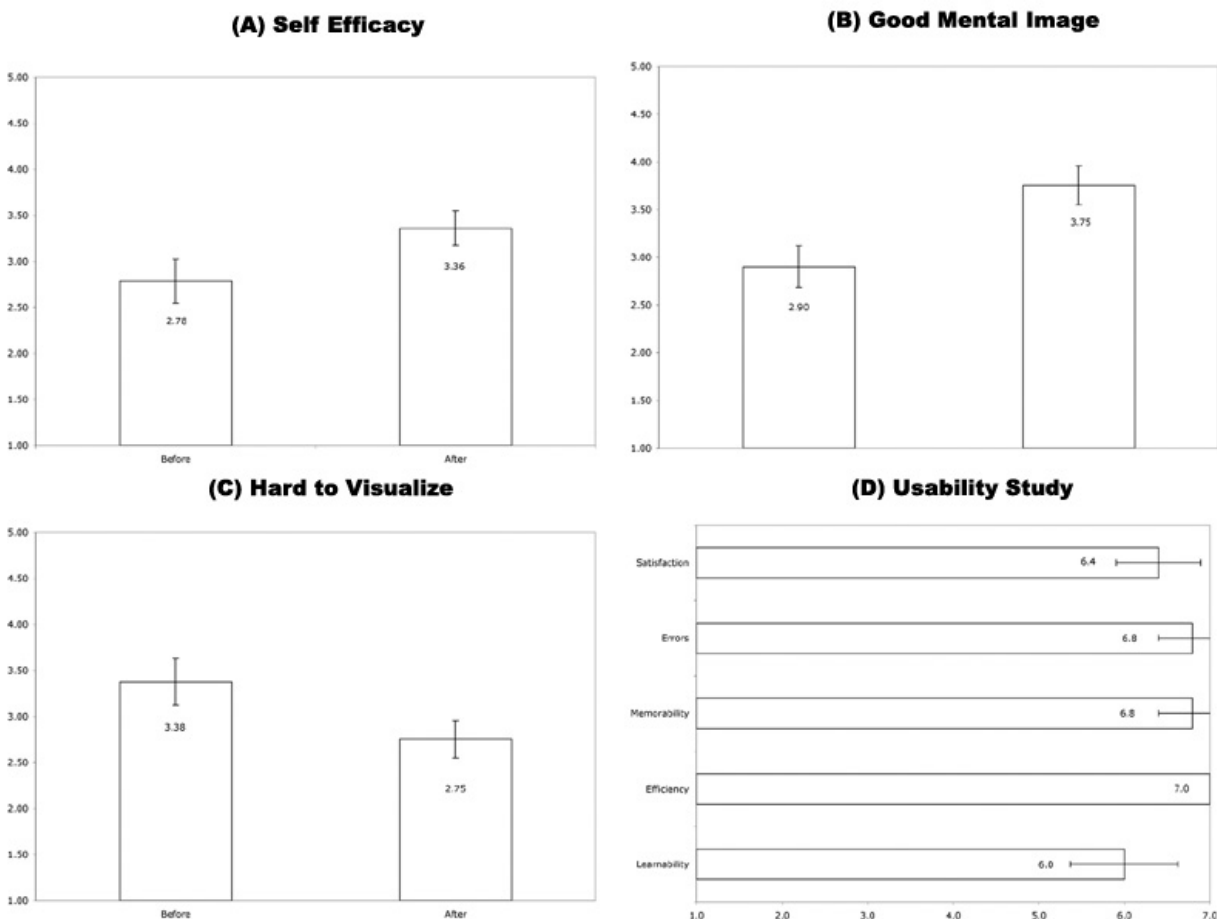


Figure 5: Before/after group results,  $n=61$ , 1=strongly disagree to 5=strongly agree. Vertical and horizontal bars are 95% confidence intervals. (A) “I feel confident in my understanding of nephron physiology.” (B) “I have a good mental image of renal physiology.” (C) “Renal physiology is hard to visualize” (D) Individual usability study,  $n=5$ , 1=unacceptable to 7=exceeds expectations.

Students agreed that the exercise gave them a good mental image of nephron physiology, with a mean rating increasing from 2.90 to 3.75 on a 5-point Likert scale (1=strongly disagree to 5=strongly agree),  $p < 0.01$  (Figure 5A). They disagreed that nephron physiology was hard to visualize, with a mean rating changing from 3.38 to 2.75 on the Likert scale,  $p < 0.01$  (Figure 5B). Students agreed that their self-confidence improved as a result of the exercise, with the mean rating increasing from 2.76 to 3.36,  $p < 0.01$  (Figure 5C). Overall, students found the game interesting (80%) and thought that it should be made a regular part of the curriculum (70%) (Figure 5D).

## Heuristic Evaluation

Four medical students and one computer science faculty member completed the evaluation. In the initial session, gaming/interface issues constituted 64% (36/56) of the open-ended comments. This increased to

93% (50/54) of the open-ended comments during the second session, suggesting that important content issues had been addressed in the revised version of the software.

## **Individual User Evaluation**

Five medical students participated in one user evaluation session each. All domains were rated at a level that, “exceeds expectations” on the Likert scale (Figure 5). This suggested that the iterative approach to software development was successful.

## **FUTURE TRENDS**

We believe that simulations will provide an increasingly realistic and effective method of teaching concepts to medical/healthcare students. Human physiology is very complex, and still not completely understood (Thomas et al., 2006). Creating models and performing simulations has the potential to help us gain a more complete understanding of how the body works, and ultimately improve patient care..

The modeling of the physiologic variables, as well as the addition of stylistic components of gaming motifs, remains a work in progress. Based on feedback from the students, the current version of the nephron game is probably most suitable for novice learners of renal physiology. Although users felt that the interface was easy to learn, the present software is probably optimally used with a knowledgeable technical facilitator present. The development of the virtual reality application for use in front of a large 3D screen makes the system amenable to greater integration into a problem-based learning curriculum that emphasizes small group interaction and formative assessment facilitated by a faculty member.

Our future plans are to integrate the kidney simulation with a more dynamic game engine. For example, by using Monte Carlo simulation, we could extend the simulation using random variables and statistics to predict how different states of kidney respond to changing physiologic conditions (Roberts, 1992). Additionally, future studies would be valuable to assess the contribution of gaming elements to student learning and satisfaction, as well as to compare the impact of immersion in this virtual system to traditional non-immersive forms of education.

## **CONCLUSION**

We have presented a working prototype of a simulation of renal physiology for use in research and teaching medical students about the kidney. Using Flatland (2008), we model the kidney particles moving in a virtual 3D simulation. The usability study results show that a multi-agent simulation of kidney function system can improve the learning progress to the medical students.

The structure and implementation of multi-agent systems in this project also have the potential to help healthcare students understand the interaction between particles and different parts of nephron using a 3D virtual reality simulation of kidney function.

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# Teaching Mass Casualty Triage Skills Using Immersive Three-dimensional Virtual Reality

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## Abstract

**Objectives:** Virtual reality (VR) environments offer potential advantages over traditional paper methods, manikin simulation, and live drills for mass casualty training and assessment. The authors measured the acquisition of triage skills by novice learners after exposing them to three sequential scenarios (A, B, and C) of five simulated patients each in a fully immersed three-dimensional VR environment. The hypothesis was that learners would improve in speed, accuracy, and self-efficacy.

**Methods:** Twenty-four medical students were taught principles of mass casualty triage using three short podcasts, followed by an immersive VR exercise in which learners donned a head-mounted display (HMD) and three motion tracking sensors, one for their head and one for each hand. They used a gesture-based command system to interact with multiple VR casualties. For triage score, one point was awarded for each correctly identified main problem, required intervention, and triage category. For intervention score, one point was awarded for each correct VR intervention. Scores were analyzed using one-way analysis of variance (ANOVA) for each student. Before and after surveys were used to measure self-efficacy and reaction to the training.

**Results:** Four students were excluded from analysis due to participation in a recent triage research program. Results from 20 students were analyzed. Triage scores and intervention scores improved significantly during Scenario B ( $p < 0.001$ ). Time to complete each scenario decreased significantly from A (8:10 minutes) to B (5:14 minutes;  $p < 0.001$ ) and from B to C (3:58 minutes;  $p < 0.001$ ). Self-efficacy improved significantly in the areas of prioritizing treatment, prioritizing resources, identifying high-risk patients, and beliefs about learning to be an effective first responder.

**Conclusions:** Novice learners demonstrated improved triage and intervention scores, speed, and self-efficacy during an iterative, fully immersed VR triage experience.

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**Keywords:** educational technology, immersive virtual reality, task performance and analysis, triage, patient simulation

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Technology enabled learning systems (TELS) comprise a spectrum of digital learning activities that have the potential to be effective and efficient in training first responders to respond to mass casualty incidents.<sup>1</sup> TELS incorporate traditional computer-based training activities, but also include unusual technologies such as immersive virtual reality (VR). TELS are appealing as educational tools for first responder training because they can be tailored to unique situations, provide engaging learning experiences, and be reused.<sup>2,3</sup> In

2005, only 14 of 198 federal training courses on terrorism utilized TELS; only 31% were simulation-based, and only 6% used VR systems.<sup>2</sup>

Because of the paucity of VR systems, few studies have measured learning effects in VR environments. In one recent study, the knowledge structure of medical students triaging a single head trauma patient showed significantly higher gain using a fully immersed VR system with a head-mounted display (HMD) compared to using a partially immersed (computer screen) system.<sup>4</sup> We wanted to explore how novice learners would perform when encountering multiple simulated casualties in a fully immersed VR environment. Do they become faster and more accurate in triaging the patients after practice and feedback? Do they improve in their application of lifesaving interventions? Additionally, we wanted to determine whether their perceived self-confidence regarding first responder skills was affected

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by the VR experience. To conduct the study, we used a novel, fully immersive VR environment, in which the learners wore a HMD and interacted with multiple simulated casualties using a gesture-command system rather than a computer joystick or mouse. The study hypothesis was that learners would improve in speed, accuracy, and self-efficacy.

## METHODS

### Study Design

This was a repeated-measures model of task completion in a VR environment, with subjects serving as their own controls. The study flow is shown in Figure 1. The University of Hawaii Committee on Human Studies and the United States Army Medical Research and Materiel Command Human Subjects Research Review Board approved the research protocol. All participants signed written informed consent.

### Study Setting and Population

The study took place in a medical school simulation center and used a convenience sample of medical student volunteers who were recruited by a single e-mail announcement. Mass casualty triage training is not part of the medical school curriculum or clinical rotations. Twenty-four subjects were recruited and enrolled.

### Study Protocol

Students were required to achieve a baseline level of triage knowledge before they could begin the hands-on portion of the study. This consisted of listening to and viewing three instructional podcasts for a total of 15:48 minutes, followed by a 20-question graded exam. A score of equal or greater than 85% correct answers was required to continue.

During the VR portion of the study, one investigator ran the VR computer program and made sure that the subjects did not trip while wearing the HMD. Learners received a scripted orientation to the VR program and then spent about 5 minutes practicing the gesture-based commands in a test scene. After completing each VR triage scenario, the HMD was removed and learners watched a short DVD movie (iDVD, 2007, Apple Inc., Cupertino CA) that demonstrated a standardized expert approach to triage within the VR scene.

**Technology.** The VR scene was created using Flatland (University of New Mexico, Albuquerque NM),<sup>5</sup> an

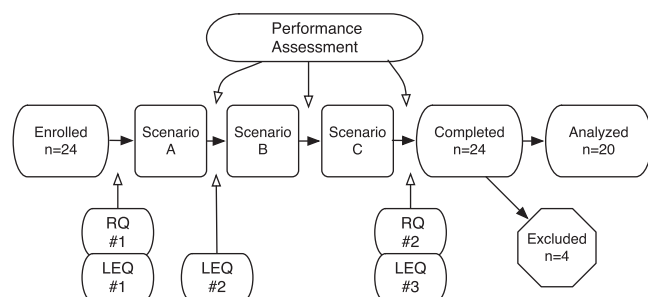
open-source information visualization system that runs on Linux OS (<http://www.linux.org/>). Visual and audio content were rendered in active stereo mode. Users wore a Fifth Dimension Technologies (5DT, Inc., Irvine CA) HMD, stereo earphones, and three motion tracking sensors (Ascension Technology Corporation, Burlington VT), one for the head and one for each hand (Figure 2). Each triage scenario consisted of five casualties with various injuries situated in a dark room. Although auditory and visual distracters are possible in the VR scene, such as police sirens, helicopters with lights, and alarms, the distracters were turned off for this exercise. Users examined VR patients (Figure 3) and engaged virtual instruments and supplies by using a pose- and gesture-based command system. For example, when a user raised his or her left hand overhead, a virtual equipment tray appeared, and the subject could then “pick up” a virtual instrument using the right hand and could then use the virtual instrument or perform an intervention on a VR casualty. VR casualties were not programmed to respond to interventions. After



**Figure 2.** A medical student, wearing a head-mounted display (HMD) and two sensor gloves checks the pulse of a simulated casualty in the virtual environment.



**Figure 3.** The same student checks a simulated casualty's carotid pulse in the virtual environment, using a virtual hand that is mapped to the right sensor glove. The fingers of the virtual hand move up and down at the pulse rate when positioned over the carotid, radial, or femoral regions. Pulse rate and strength also appear in the left upper visual field of the head-mounted display (HMD). Some students described “feeling” the pulse of the VR patient.



**Figure 1.** Study design. RQ = reaction questionnaire; LEQ = learner evaluation questionnaire.

completing an intervention, subjects assigned each VR casualty to a triage category using a four-color triage tag within the VR environment. They also selected the main problem and main required intervention from a pick list. The gesture-based command system has been described in greater detail elsewhere.<sup>6</sup> When triage was completed, subjects were automatically transported to the next simulated casualty without needing to navigate within the VR scene. A short video of a subject triaging five VR casualties may be viewed at <http://bloodgoesroundandround.com>.

**Scenarios.** Three scenarios consisting of five adult casualties were created in the VR world. Each scenario consisted of three “immediate” patients, one “minimal” patient, and one “delayed or expectant” patient. The immediate injuries were one hemorrhagic shock, one tension pneumothorax, and one airway management problem. Delayed casualties included a patient with a leg fracture and a patient with blunt abdominal trauma. One “expectant” casualty had massive head trauma and anisocoria. Minimal patients had minor wounds with normal vital signs. Learners were required to identify the main abnormality (one or none), perform an intervention (one or none), and place each casualty into the appropriate triage category. Main abnormalities fell into these categories: airway, breathing, circulation, neurologic, and “other” (such as fracture or psychological injury). Intervention options included applying a tourniquet, using a HemCon (HemCon Medical Technologies, Inc., Portland OR) bandage, applying a regular bandage, performing a needle chest decompression, and inserting a nasopharyngeal airway. In some instances, “no intervention” was the appropriate response.

### Outcomes

Three outcomes were measured for each scenario: triage score, intervention score, and time to triage. For triage score, 1 point was given for each correct answer that was selected by the learner in the VR environment: 1) was the main problem correctly identified, 2) was the required intervention correctly identified, and 3) was the triage category correctly identified? Thus, each learner could receive a maximum of 15 points per scenario. For intervention score, 1 point was awarded for each intervention that was performed correctly in the VR environment. Thus, each learner could receive a maximum of 5 points per scenario.

**Learner Satisfaction and Self-efficacy.** Subjects completed a reaction questionnaire<sup>7</sup> (RQ) for the completed VR experience. The RQ is an instrument that has been used to assess learner satisfaction with Web-based training material. The questionnaire was adapted to assess the relevance of the training to the learner’s perceived role as a first responder rather than to the learner’s usual clinical role. Subjects completed a self-efficacy questionnaire before the VR experience, after Scenario A, and after Scenario C. The questionnaire was modeled after the learner evaluation questionnaire (LEQ), an instrument designed to measure medical student attitudes toward curriculum.<sup>8</sup> We modified a

subscale of the LEQ, the self-efficacy scale. The questions were changed to take the viewpoint of a first responder instead of a medical student. Two additional self-confidence questions were included. Each question was scored on a 5-point Likert scale with points labeled “never” (1) to “always” (5; Table 1).

### Data Analysis

Learners served as their own controls. The design was a repeated-measures model comparing task completion between scenarios. Previous simulation research with manikins<sup>9</sup> demonstrated that task completion was improved most between the baseline and subsequent scenario, with a difference of about 30%. Thus, for a correlation of  $r = 0.80$ , 20 subjects were required (tested against a constant correlation of  $r = 0.50$ ,  $\beta = 0.80$ ,  $\alpha = 0.50$ , tails = 2; source of estimation, SPSS Sample Power, SPSS Inc., Chicago IL). Results are reported as mean  $\pm$  standard deviation (SD). Times were compared between the three scenarios using one-way analysis of variance (ANOVA) for each student. Triage score and intervention score were analyzed using one-way ANOVA for each student. Self-efficacy questions were analyzed using one-way ANOVA for each student. Post hoc analysis was performed using Scheffe’s correction.

## RESULTS

### Demographics

Twenty-four students scored  $>85\%$  on the didactic test and completed the VR exercise. Four of the students were subsequently excluded from the analysis because they had participated in a manikin-based triage research project within 6 months that used similar

Table 1  
Self-efficacy

	Before	After	p Value
1. I feel confident that I will learn to be an effective first responder.	4.0 (0.69)	4.2 (0.62)	0.034
2. I feel confident that patients will consider me an effective first responder.	3.8 (0.64)	4.1 (0.60)	0.006
3. I feel confident in my ability to prioritize the treatment of patients in a mass casualty situation.	3.2 (0.89)	4.2 (0.52)	0.001
4. I feel confident in my ability to prioritize the use of resources in a mass casualty situation.	3.1 (0.97)	4.2 (0.75)	0.001
5. I feel confident in my ability to identify high risk patients for immediate treatment in a mass casualty situation.	3.4 (0.88)	4.2 (0.77)	0.008
Data are reported as mean ( $\pm$ SD). 5-point Likert scale: 1 = never to 5 = always.			

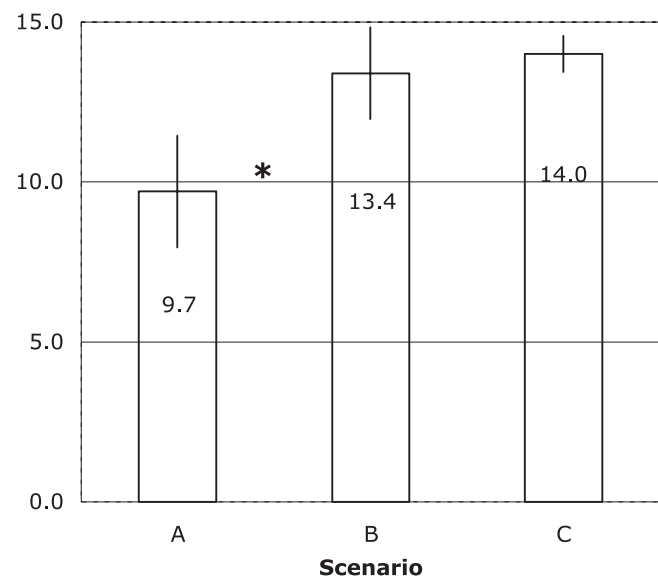
triage scenarios. Most learners were in their first year of medical school (MS1; 12/20; 60%), but the study also included 3 MS2 (15%), 3 MS3 (15%), and 2 MS4 (10%) learners.

All five self-efficacy questions showed a statistically significant increase in scores over time. Students became more confident that their patients would consider them effective first responders ( $p = 0.006$ ), more confident in prioritizing treatment ( $p = 0.001$ ), more confident in prioritizing resources ( $p = 0.001$ ), and more confident in identifying high-risk patients ( $p = 0.008$ ). Students expressed initial confidence that they would be able to learn how to be an effective first responder, and this score also increased ( $p = 0.034$ ; Table 1).

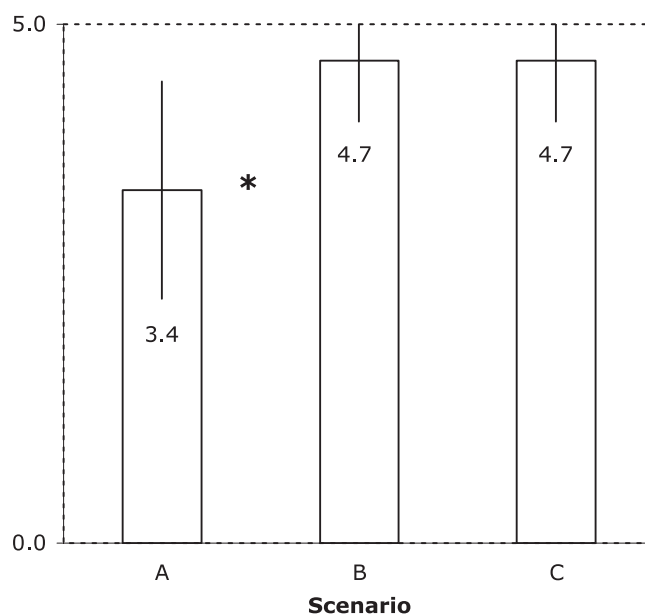
Triage score improved significantly from Scenario A to Scenario B, but not from Scenario B to Scenario C (Figure 4). The 26% improvement from A to B was felt to be clinically significant. The intervention score also improved significantly from Scenario A to Scenario B, but not from Scenario B to C (Figure 5). The average improvement between Scenario A and Scenario B of more than one correct intervention for five simulated casualties was felt to be clinically significant. Time to triage improved from Scenario A to Scenario B and from Scenario B to Scenario C (Figure 6). The overall improvement by 4:12 minutes is likely to be clinically significant.

### VR Training Evaluation

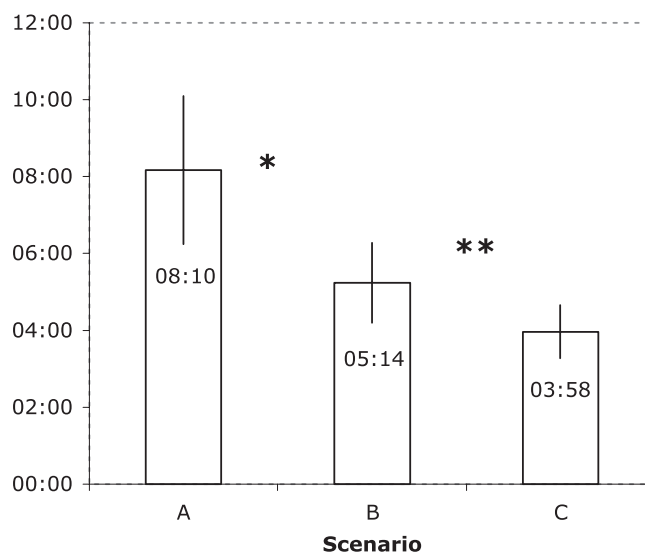
The students rated the simulation phase of the course highly (Table 2). They also felt that the pace was just right ( $4.2 \pm 0.39$  on 7-point Likert scale, 1 = too slow and 7 = too fast). The level of difficulty was also rated as good ( $4.5 \pm 0.83$  on 7-point Likert scale, 1 = too easy and 7 = too hard). The students also agreed that the course was relevant to them as health care providers ( $6.5 \pm 0.61$  on 7-point Likert scale, 1 = strongly disagree, 7 = strongly agree).



**Figure 4.** Average triage score per learner (maximum = 15). Lines and numbers in bars are standard deviations (SDs). \* $p < 0.001$ . y-Axis label = triage score.



**Figure 5.** Average intervention score per learner (maximum = 5). Lines and numbers in bars are standard deviations (SDs). \* $p < 0.001$ . y-Axis label = intervention score.



**Figure 6.** Time to triage one scenario consisting of five simulated patients. Line and numbers in the bars represent standard deviations (SDs). \* $p < 0.001$ , \*\* $p < 0.05$ . y-Axis label = time to triage.

### DISCUSSION

We showed that novice learners improved their performance in the VR environment after two iterations of VR training, with triage and intervention scores improving significantly during the second scenario. Learners worked significantly faster with each new set of VR patients, with time to triage improving significantly with each additional scenario. Learners also reported increasing levels of self-confidence throughout the exercise. Students reported that they were more confident in prioritizing treatment, prioritizing resources,

**Table 2**  
Evaluation of VR Triage Course

	VR Simulation
1. The material covered was relevant to my duties as a health care team member.	6.5 (0.61)
2. The course objectives were adequately explained.	6.3 (0.97)
3. The course was well organized.	6.5 (0.69)
4. The material was presented in an interesting way.	6.8 (0.55)
5. The course communicated the material effectively.	6.7 (0.59)
6. As the course progressed, my questions were answered.	6.8 (0.44)
Data are reported as mean ( $\pm$ SD). 7-point Likert scale: 1 = strongly disagree, 4 = neutral, 7 = strongly agree. VR = virtual reality.	

and identifying high-risk patients for treatment. They were also more confident that their patients would consider them an effective first responder. Self-efficacy has been shown to influence learner performance<sup>10</sup> and may also predict performance on objective structured clinical examinations.<sup>11</sup>

Our application is unique in its combined use of fully immersive VR, a gesture-based command system, and multiple simulated patients. Other computer-based training systems, such as the Virtual Medical Trainer,<sup>12</sup> MediSim,<sup>13</sup> and Sim-Patient<sup>14</sup> are partially immersive, menu-driven VR applications that display the simulation on a computer screen. BioSimMER<sup>15</sup> was an immersive emergency simulation relating to a biologic attack that used a HMD and simple motion gestures for navigation; development was discontinued 8 years ago, possibly due to the complexity and high cost of the technology in 1999. The JUST VR<sup>16</sup> system was designed to simulate training under stressful conditions and uses a rear a projection system in which a virtual assistant helps the user with navigation and tasks using natural language. Project TOUCH is an immersive VR application from which our current application was derived. Learners wear an HMD and use a joystick to navigate within a VR environment occupied by a single patient with head trauma. Interestingly, TOUCH investigators recently demonstrated that fully immersed students had a higher gain in knowledge structure than students who viewed a computer screen and used a mouse to diagnose and treat the simulated patient.<sup>4</sup>

## LIMITATIONS

Students who volunteered may have been more technically sophisticated than nonvolunteers, resulting in better scores with additional VR exposure. Twenty-five percent of the subjects were students in their third or fourth year of medical school. Due to their clinical experience, they may not have been representative of most first responders and may have biased the results in favor of a greater training effect.

We introduced a new gesture-based command system for navigating in the VR environment. Some of the

performance gains that students exhibited may have been due to increasing familiarity with the human/computer interface, rather than improvement in their triage knowledge structure.

We do not know the degree to which the improvements in triage and intervention scores, time to triage, and self-efficacy in this immersive VR environment correlate with other traditional methods of teaching triage such as manikin-based simulation. We also do not know how results in this immersive VR environment would compare to more traditional computer-based simulations that are partially or nonimmersive. In future studies, we plan to compare the performance of learners in a fully immersed VR environment with performance during a manikin-based simulation.

## CONCLUSIONS

We conclude that principles of mass casualty triage can be effectively and efficiently taught to novice learners using an immersive three-dimensional VR training environment. Further studies would be valuable to determine how immersive VR training could complement or augment current mass casualty incident training methods.

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## Evaluating a Virtual Reality Motor-Skills Simulator

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**Abstract.** Evaluation was performed on a prototype low-cost virtual-reality motor-skills simulator (VRMSS) created at the Telehealth Research Institute, John A. Burns School of Medicine, in conjunction with the National Biocomputation Center, Stanford University. The VRMSS is specifically designed to teach baseline fine-motor skills used in surgery that are based on a matrix of elemental technical skills that comprise the tenets of surgical technique. Fifty-seven participants were randomly assigned to one of three groups (VRMSS, box trainer or no training). After training each group was evaluated using the LapSim from Surgical Sciences. The VRMSS and box trainer were similar in performance, but significantly better than the no training control group. The VRMSS has significant advantages over the box trainer, in that the VRMSS can provide scoring on several parameters of the task without the need of an instructor and the VRMSS is approximately 1/16<sup>th</sup> the cost of the Lapsim.

**Keywords.** virtual-reality fine motor skills simulator, laparoscopic surgical trainer

### Introduction

A prototype low-cost virtual-reality motor-skills simulator (VRMSS)<sup>1</sup> was created using the SPRING platform<sup>2</sup> as the underlying development tool at the Telehealth Research Institute, John A. Burns School of Medicine, in conjunction with the National Biocomputation Center, Stanford University. The VRMSS was specifically designed to teach baseline fine-motor skills used in surgery that are based on a matrix of elemental technical skills that comprise the tenets of surgical technique.<sup>3</sup> Following initial audio/video based instruction; bead-like objects are moved to holding cups/target areas within a non-threatening abstract 3-Dimensional environment in laparoscopic, microscopic, and endoscopic formats (see Figure 1). The use of haptics (touch, force-feedback) provides more human-computer interaction and realism than previously possible for personal-computer applications. Complexity is increased or decreased by changing the following factors: requirement for non-dominant or bimanual hand use and environmental changes (depth of field, decreased exposure, and obstacles). This

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evaluation of the VRMSS was funded by the Telemedicine and Advanced Technology Research Center.



**Figure 1.** The VRMSS laparoscopic trainer for grasping, lifting & grasping and coordination skills is shown with dual force-feedback controllers.

## 1. Tools and Methods

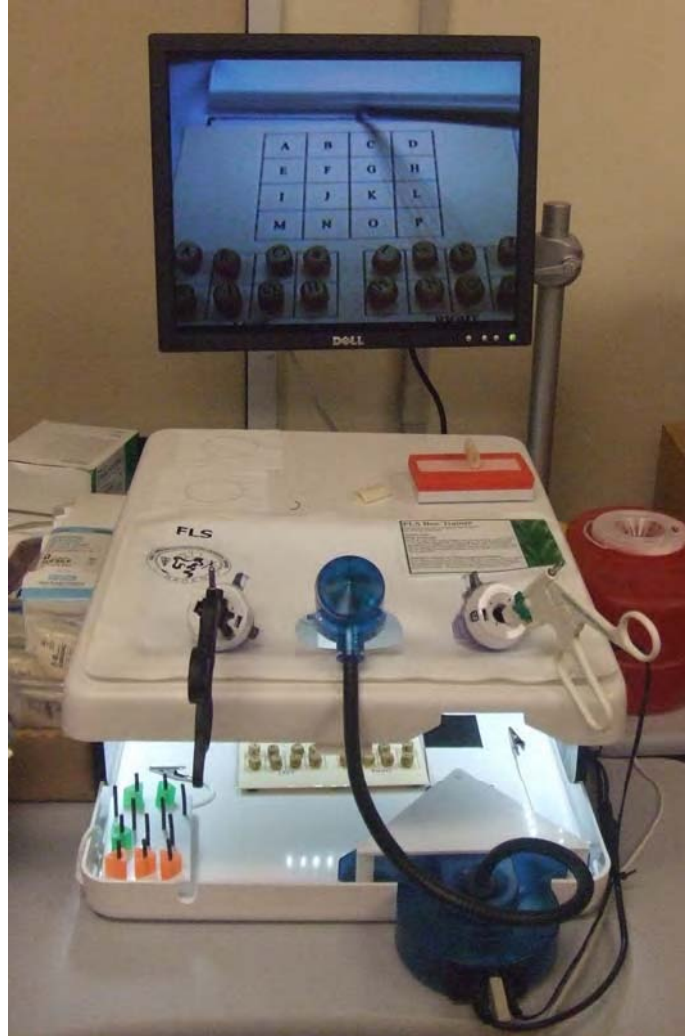
Fifty-seven participants were randomly assigned to one of three groups to conduct an evaluation study of the VRMSS. To assess fine-motor skills participants performed the basic skills of grasping, lift & grasping and coordination on the LapSim from Surgical Sciences<sup>4</sup> (see Figure 2). Each group then received time-equivalent training. The first group trained on the VRMSS. The second group trained on a box trainer used for laparoscopic training (see Figure 3). The third, control group, read through two chapters of online curriculum on telemedicine<sup>5</sup>. Participants were then reassessed on the LapSim for changes in fine-motor surgical skills.



**Figure 2.** LapSim from Surgical Sciences.

## 2. Results

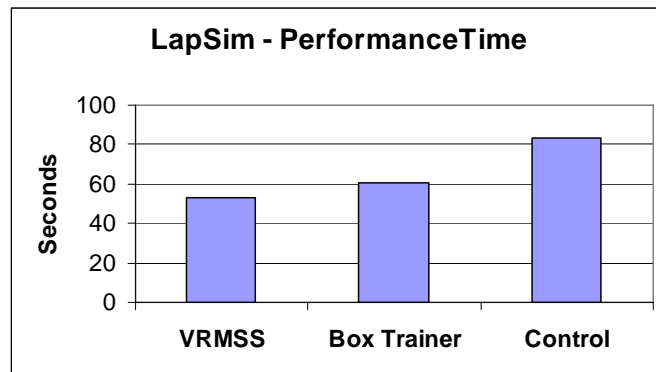
The grasping and lifting & grasping tasks were not significantly difficult and all groups performed well on those tasks. Figures 4 and 5 show highlights of group performance on the LapSim coordination task after training. Group performance times in Figure 4 show a significant difference between the groups (mean = 66.3 seconds,  $F=3.423$ ,  $p<0.04$ ). The post hoc test (Tukey) showed that VRMSS and the box trainer mean completion times were not significantly different and the control group had a significantly longer performance time ( $p<0.044$ ). Figure 5 shows the pass percentage for the groups. The VRMSS and box trainer groups were very similar and both training were at least 1.75 times better than the control group.



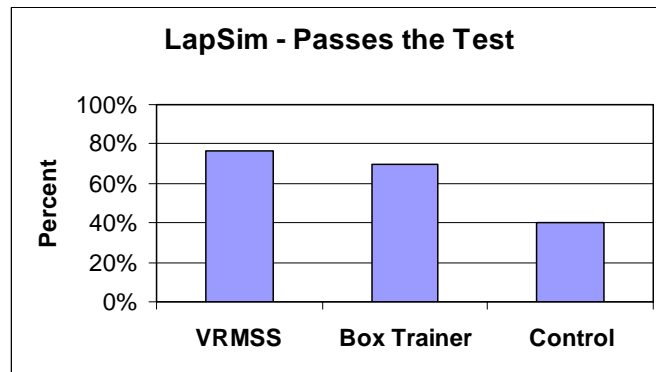
**Figure 3.** Box trainer used for laparoscopic training.

### 3. Discussion

Training on both the box trainer and LapSim have been previously shown to positively impact operating room performance,<sup>6,7</sup> With the VRMSS and box trainer groups having similar results on the LapSim assessment, it is likely that VRMSS would also have a positive impact on outcomes at surgery. However, like LapSim, VRMSS has significant advantages over the box trainer, in that the VRMSS can provide scoring on several parameters without the need of an instructor during student skill acquisition. Parameters of importance scored by the VRMSS include: time to complete task, number of errors and economy of movements.<sup>8</sup> Also, the VRMSS is approximately 1/16th the cost of the LapSim.



**Figure 2.** Shown is the mean time of each group on the coordination task after receiving training.



**Figure 3.** Shown is the percent of participants from each group that passed the LapSim on the coordination task after receiving training.

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- [8] Kihmm Connolly, K., Aschwanden, C., Burgess, L., and Peters, D., A Feasibility Study for the Validation of the Virtual Reality Motor-Skills Simulator, The 16th Annual Medicine Meets Virtual Reality Conference, Long Beach, California, USA, February 6 - 9, 2007.



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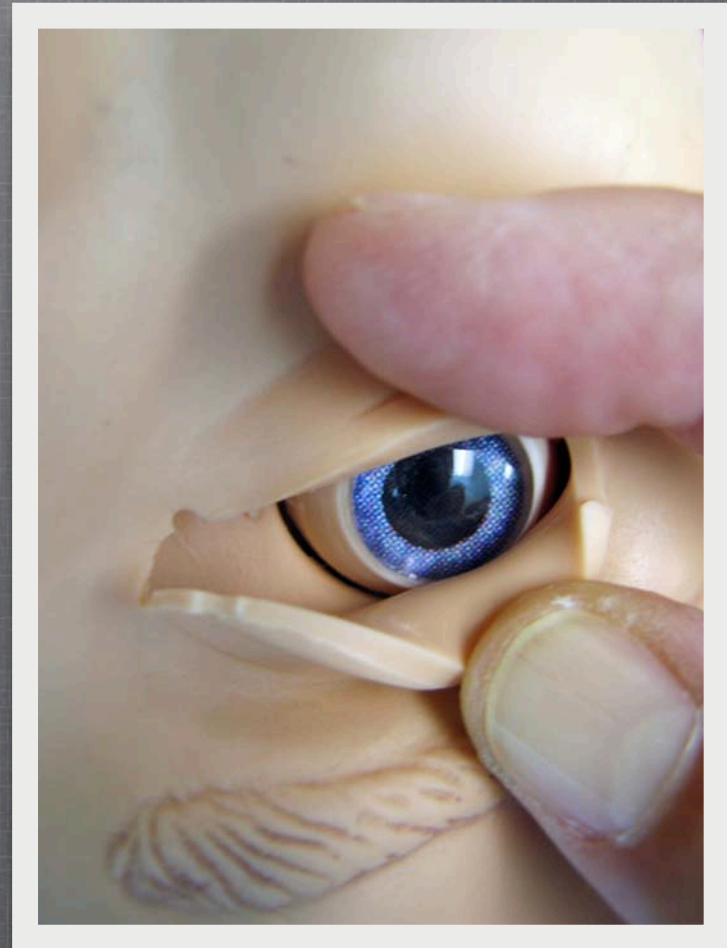
*University of Hawaii*



## Appendix D

# AGENDA

Manikin Triage  
Virtual Reality Triage  
Virtual Nephron  
LapSim Experiment  
Tangible User Interface  
Augmented Reality

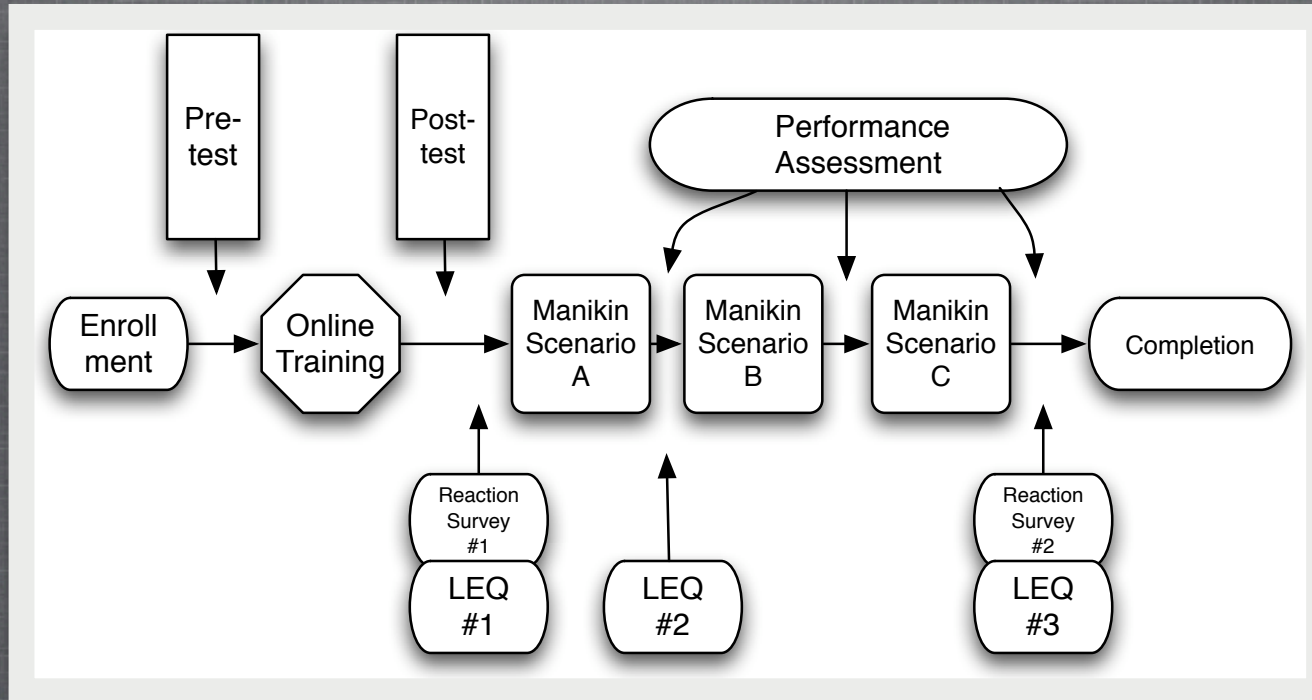


# PODCASTS

- Triage Podcasts
  - Introduction to Manikin Triage
  - Principles of Mass Casualty Triage
  - Triage Challenge I
  - Triage Challenge II



## MASS CASUALTY TRIAGE TRAINING

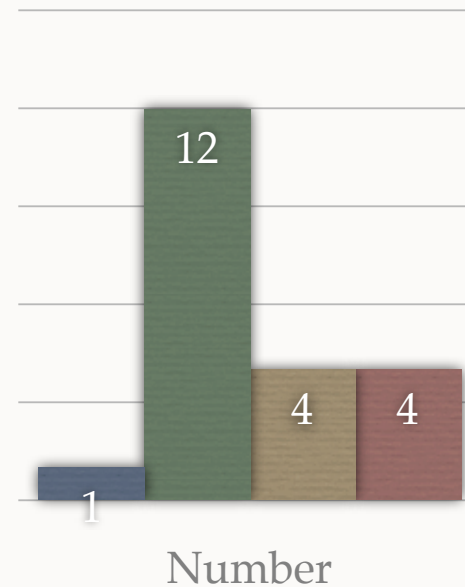


## STUDY DESIGN

# MANIKIN TRIAGE

- 21 students were enrolled
- Most were 2nd year students
- All were novices (without prior triage training)

■ MS1 ■ MS2 ■ MS3 ■ MS4

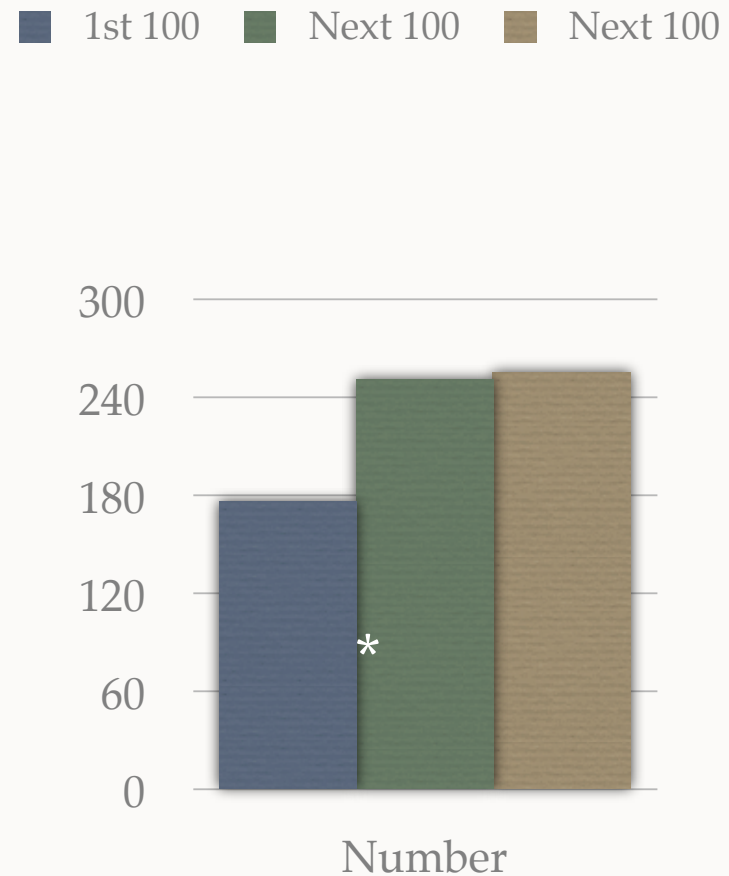


# TAGGING ACCURACY

## MANIKIN TRIAGE

- 3 correct responses per simulated patient
- 300 possible correct answers for 20 students
- Students were more accurate after 10 simulated patients

$p < 0.001$

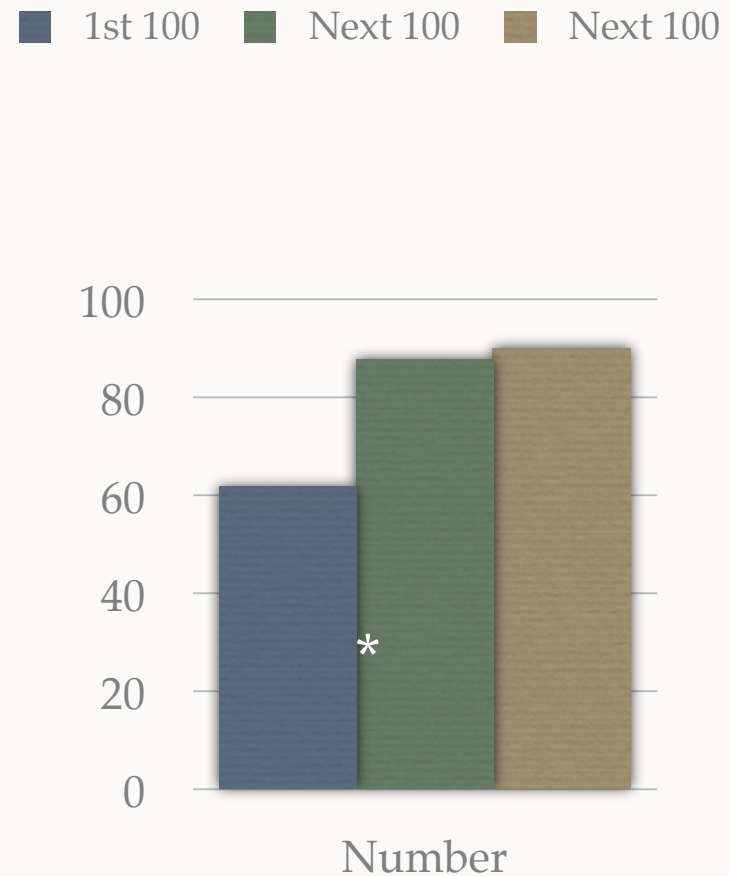


# INTERVENTION ACCURACY

## MANIKIN TRIAGE

- One correct intervention for each of five simulated patient
- Students intervened more appropriately after 10 simulated patients

$p < 0.001$



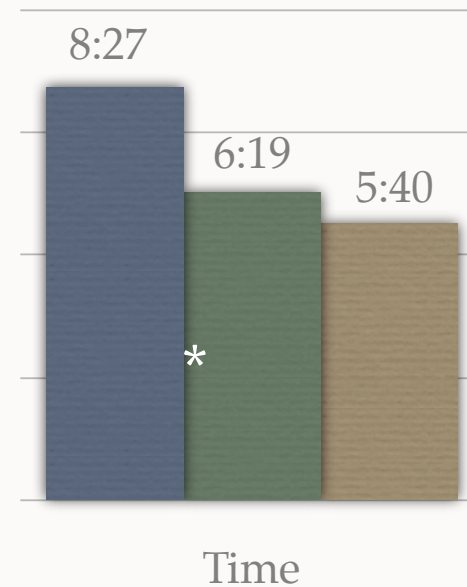
# SPEED

## MANIKIN TRIAGE

- Time to triage 5 simulated patients
- Students got faster after 10 simulated patients

■ 1st 5 patients ■ Next 5 ■ Next 5

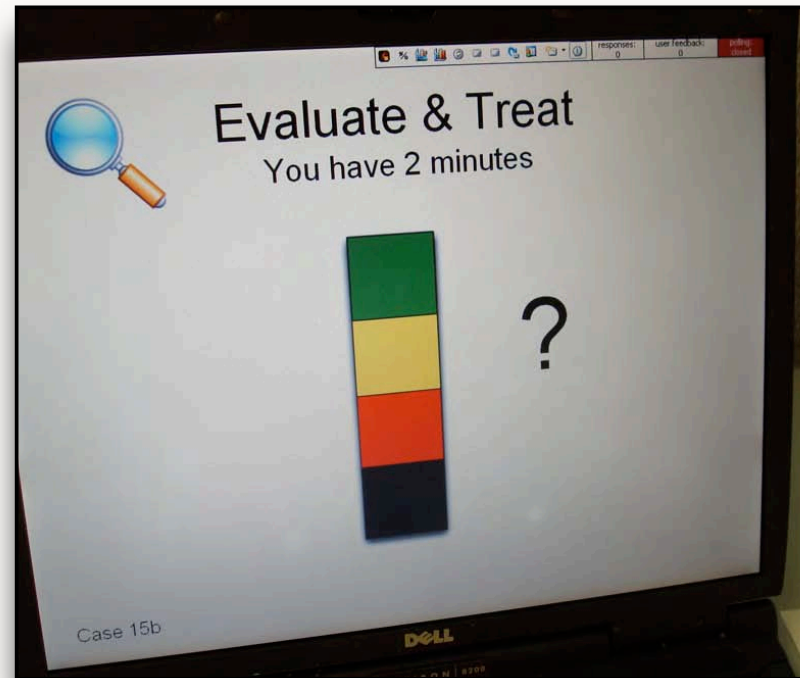
$p < 0.001$



# TRIAGE COURSES

## Adaptations of Triage Experiment

- 318 learners have taken triage courses
- JABSOM
- Japan, Korea, Thailand, Vietnam, Philippines
- US Navy Medics with Marine units





US MARINES

*SHOCK TRAUMA AIRWAY TASK TRAINING - STATT*



STATT

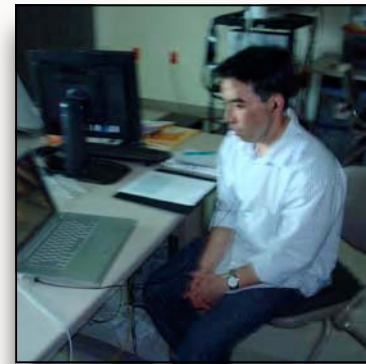


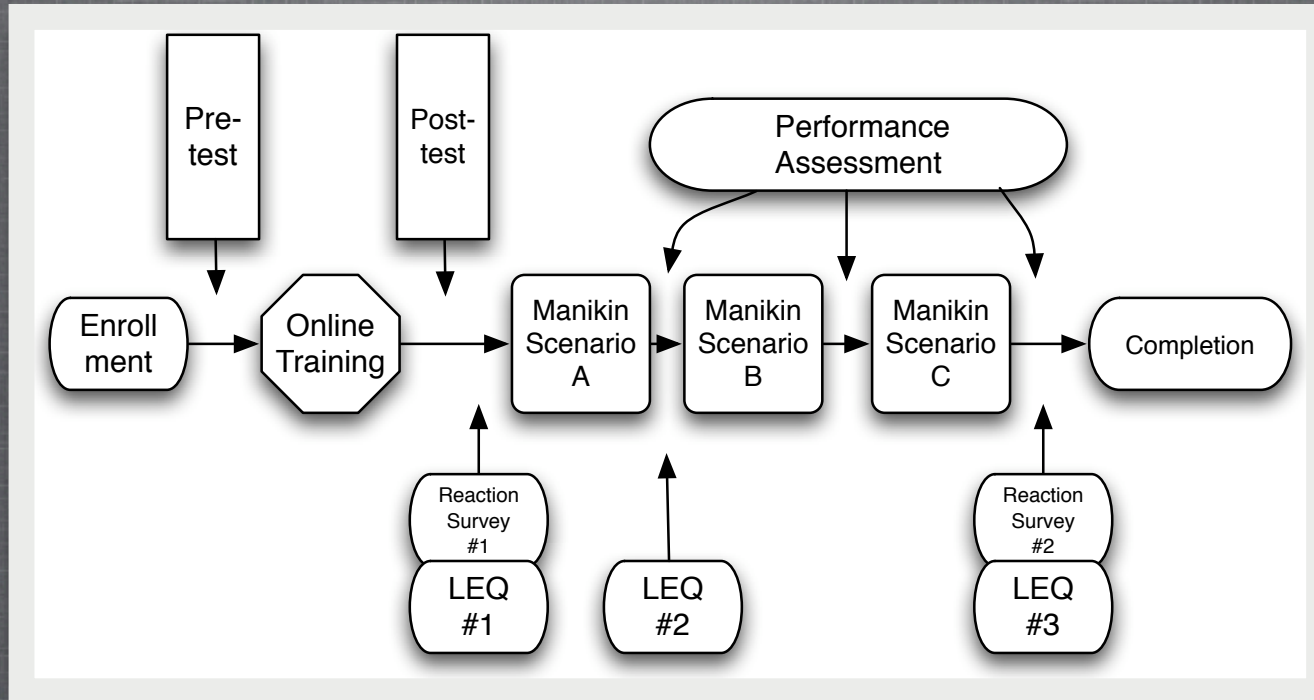
STATT

*Audience Response System used for Group Debriefing*

# VIRTUAL REALITY TRIAGE

- VR Triage with Medical Students
- VR Triage Movie





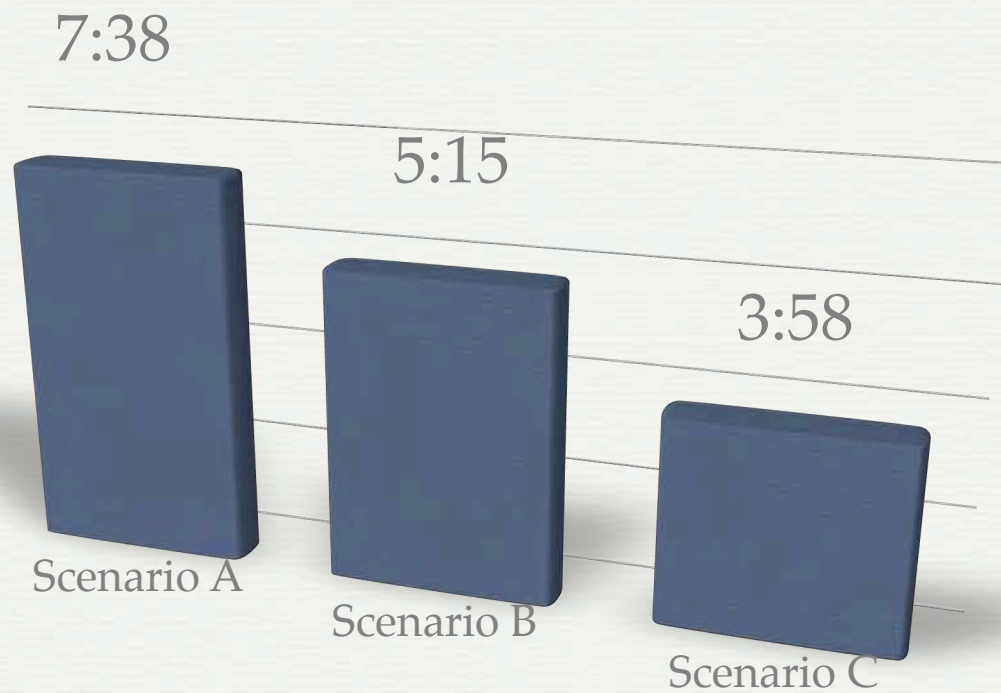
## STUDY DESIGN

# SPEED

## VR TRIAGE

### VR Triage Study

■ Minutes

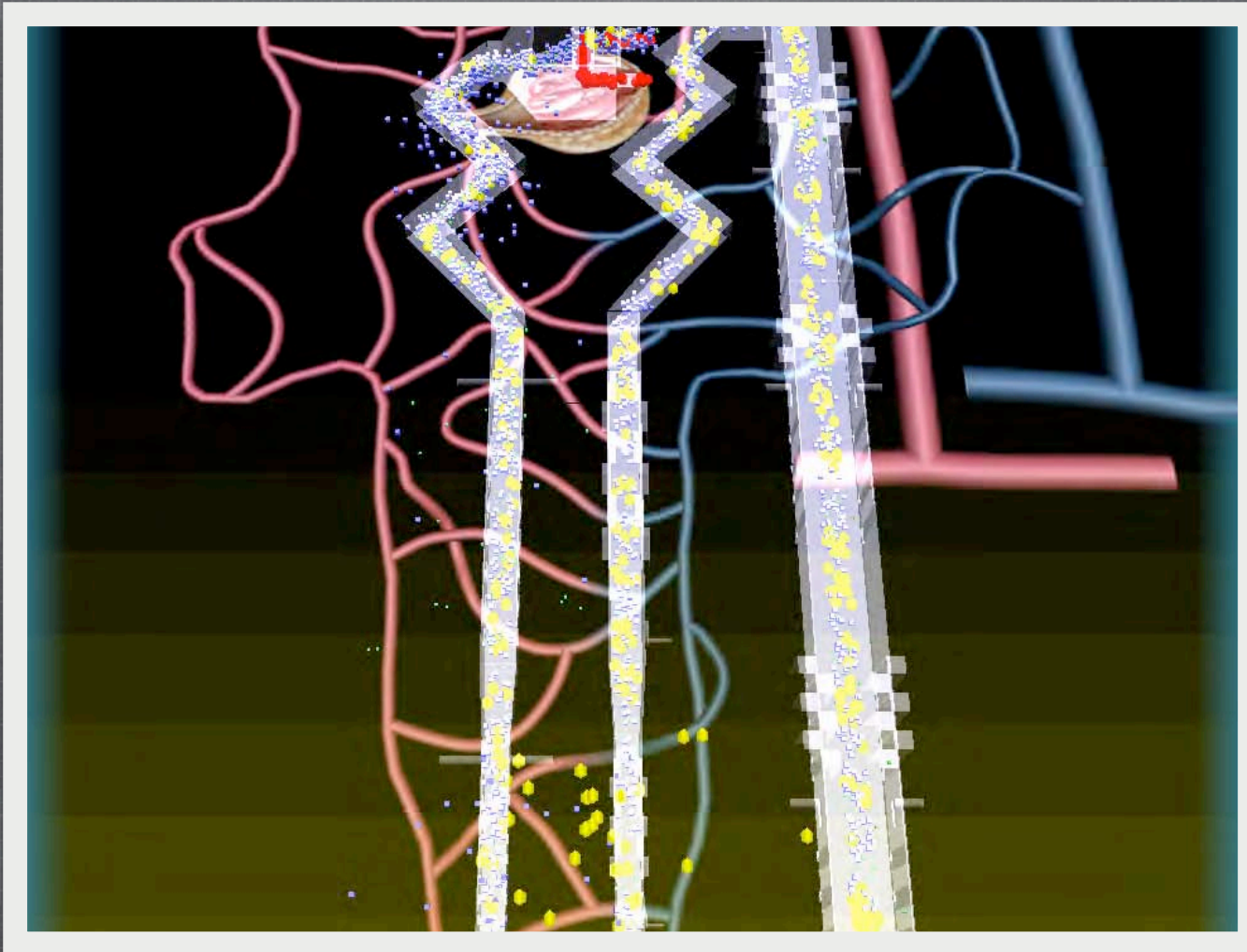


## VR TRIAGE SELF-EFFICACY

I FEEL CONFIDENT THAT I WILL . . .

### Improved Self-Efficacy after VR Triage

- \*My patients will consider me an effective first responder
- \*Be able to prioritize the treatment of patients in a mass casualty situation
- \*Be able to prioritize the use of resources in a mass casualty situation
- \*Be able to identify high risk patients for immediate treatment in a mass casualty situation
- \*statistically significant results

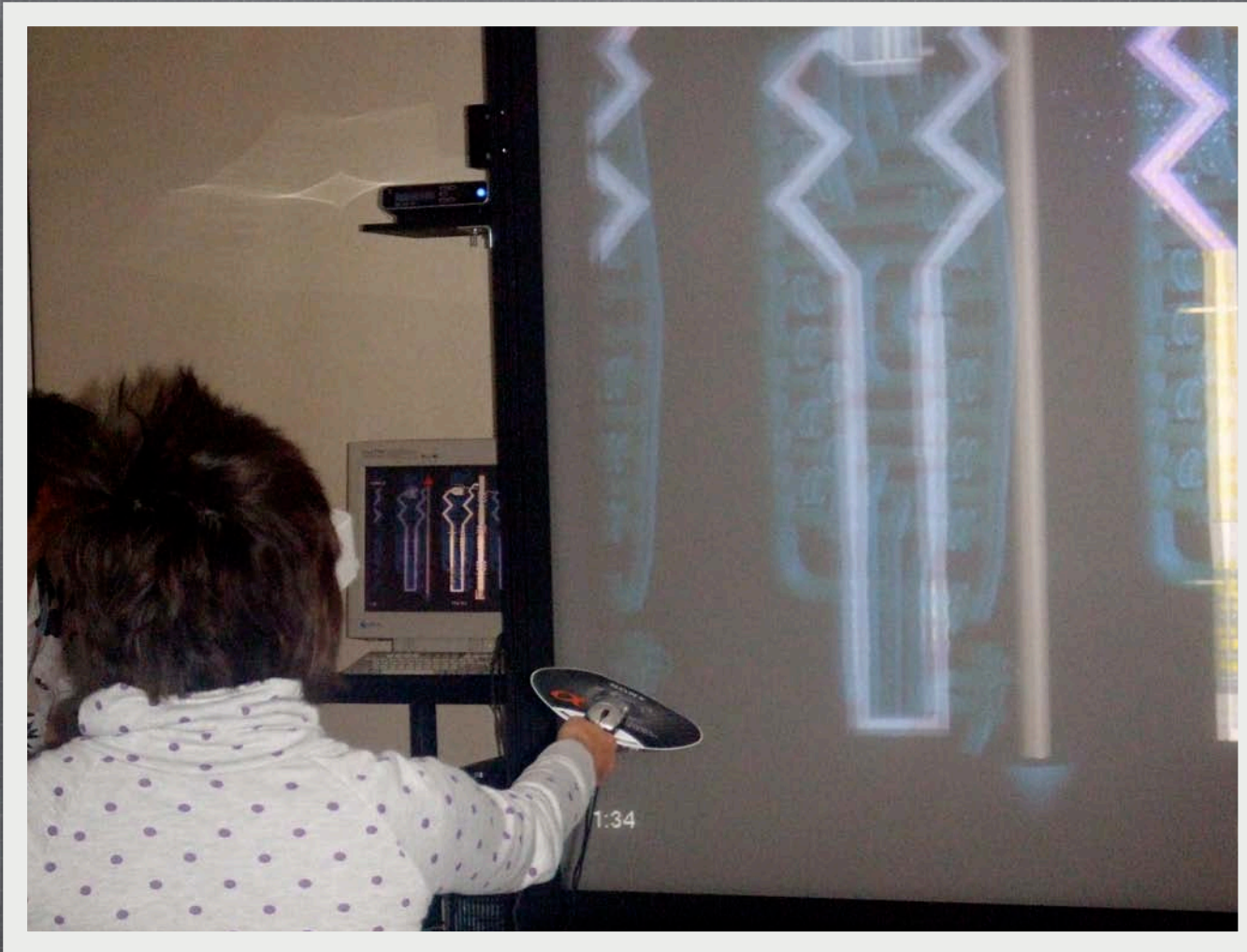


## VIRTUAL REALITY NEPHRON

# USER EVALUATION

## VR Nephron Experiment

- 60 first year medical students
- Cardiovascular - renal unit
- 6 facilitated sessions (tutorial groups)
- 45 minutes each



## USER INTERFACE

*Student uses a paddle to select objects in the nephron model*



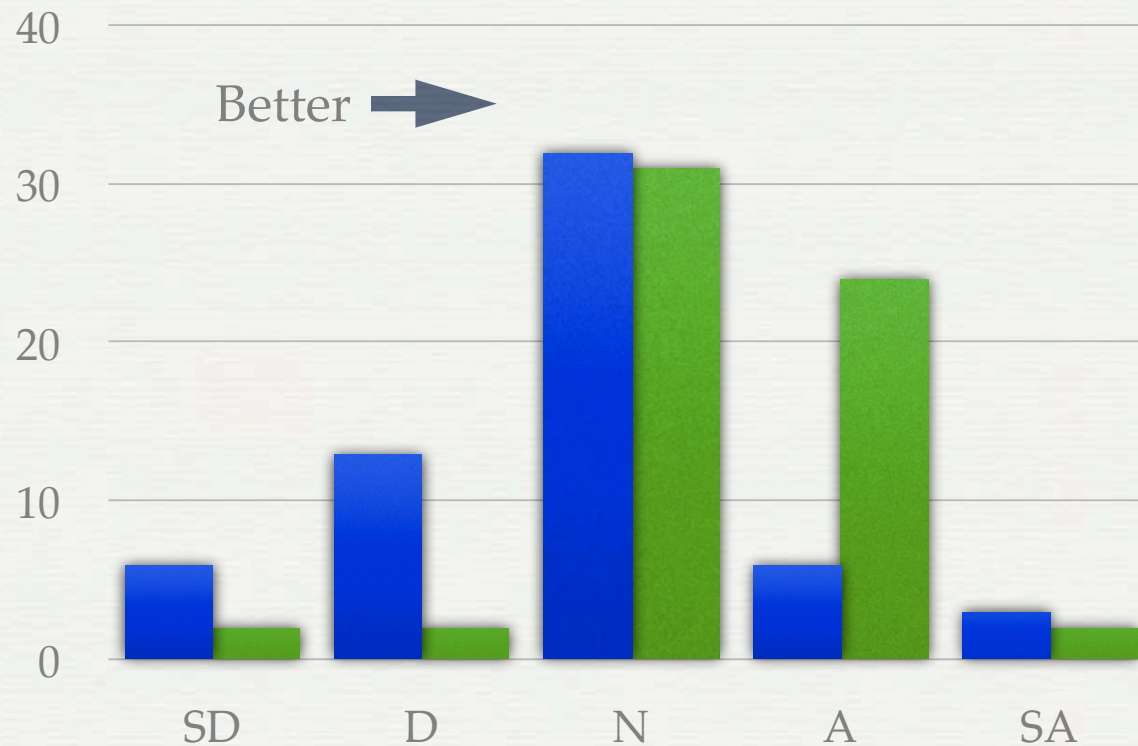
## FACILITATED SESSION

*Student navigates to locations that demonstrate physiologic principles*

■ Before

■ After

I feel confident in my understanding  
of renal physiology . . .

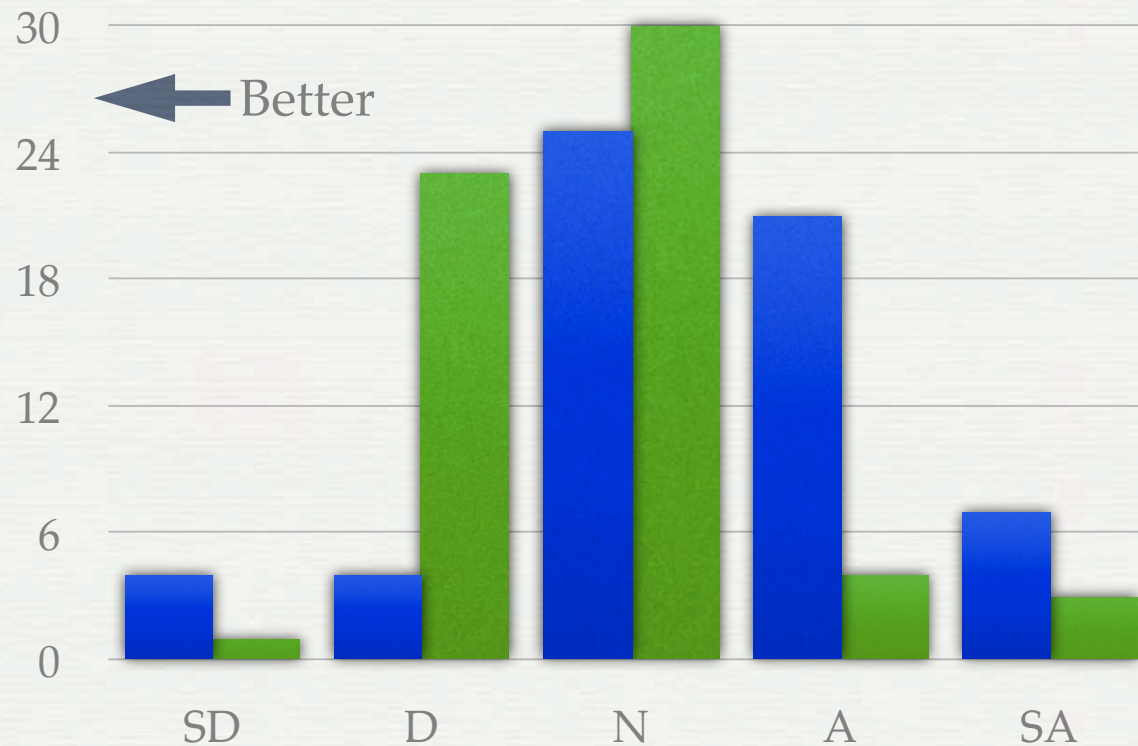


SD=Strongly Disagree, D=Disagree, N=Neutral, A=Agree, SA=Strongly Agree

■ Before

■ After

Nephron physiology is hard  
for me to visualize . . .

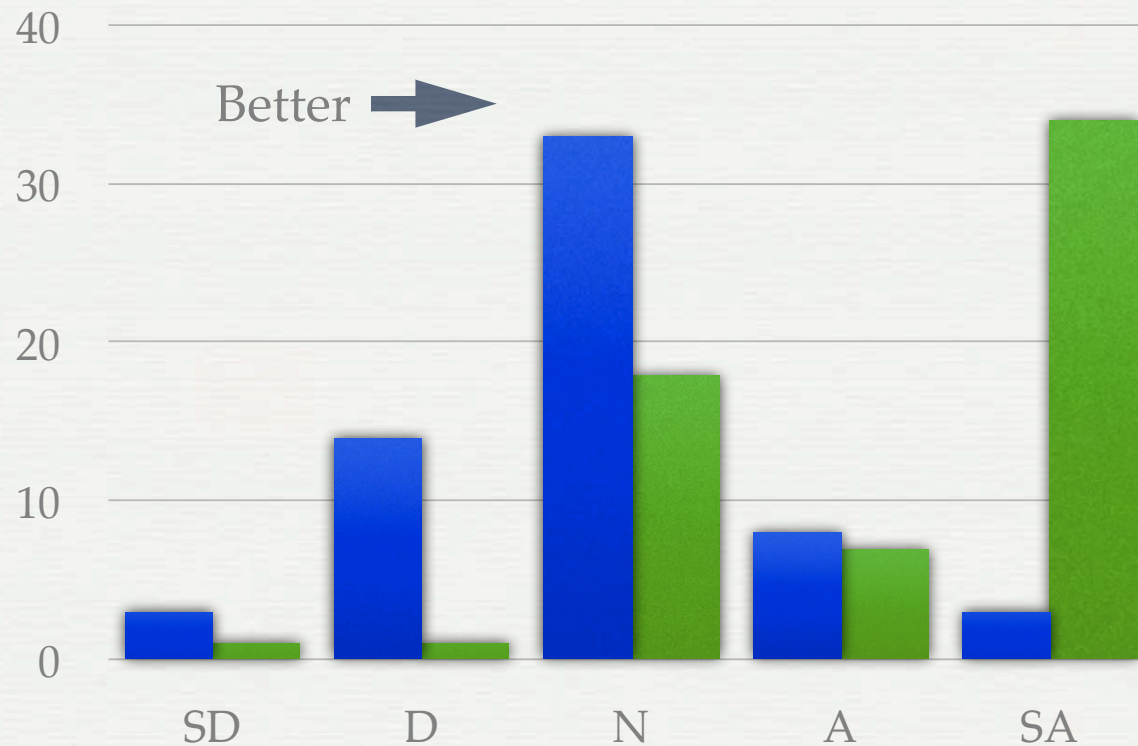


SD=Strongly Disagree, D=Disagree, N=Neutral, A=Agree, SA=Strongly Agree

■ Before

■ After

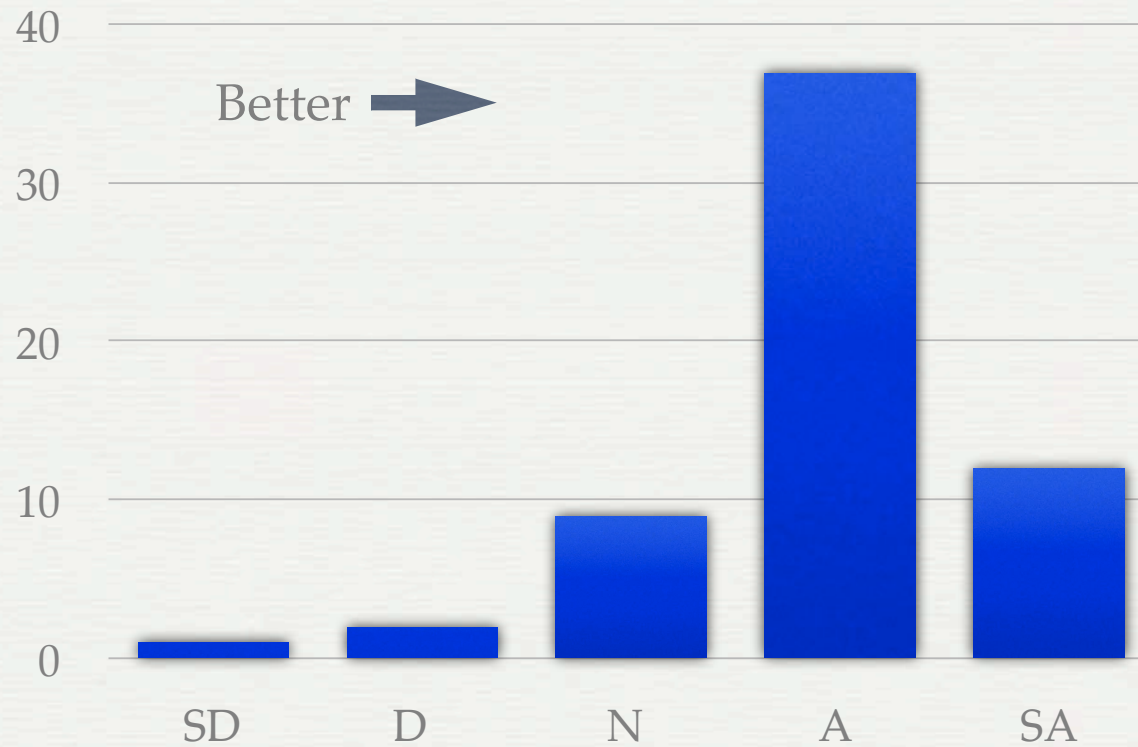
I have a good mental picture  
of nephron physiology . . .



SD=Strongly Disagree, D=Disagree, N=Neutral, A=Agree, SA=Strongly Agree

■ After

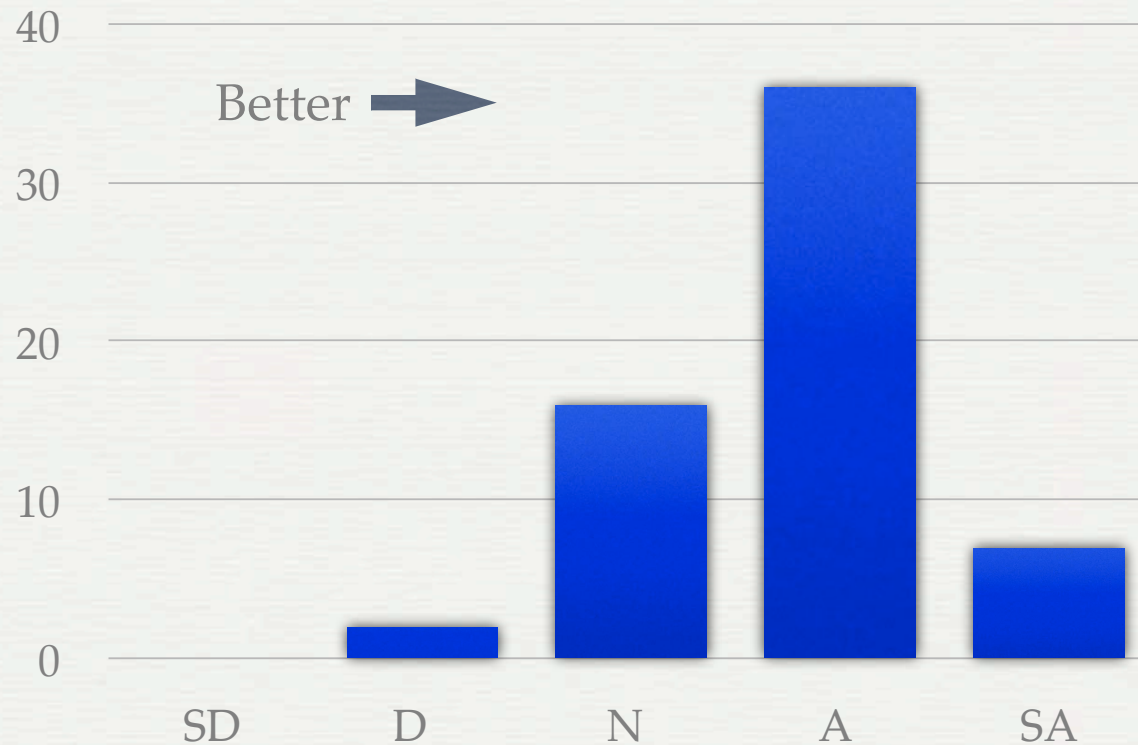
I found the nephron game interesting . . .



SD=Strongly Disagree, D=Disagree, N=Neutral, A=Agree, SA=Strongly Agree

■ After

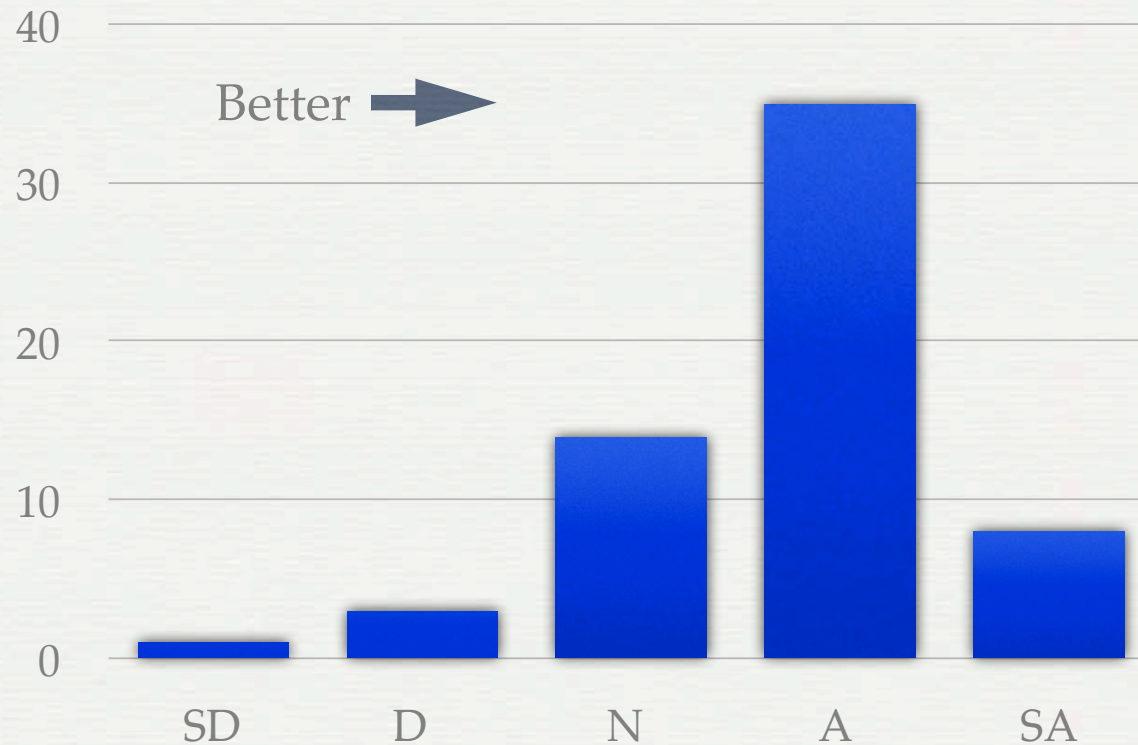
The nephron game helped me learn  
nephron physiology . . .



SD=Strongly Disagree, D=Disagree, N=Neutral, A=Agree, SA=Strongly Agree

■ After

The nephron game should become  
a regular part of the curriculum . . .



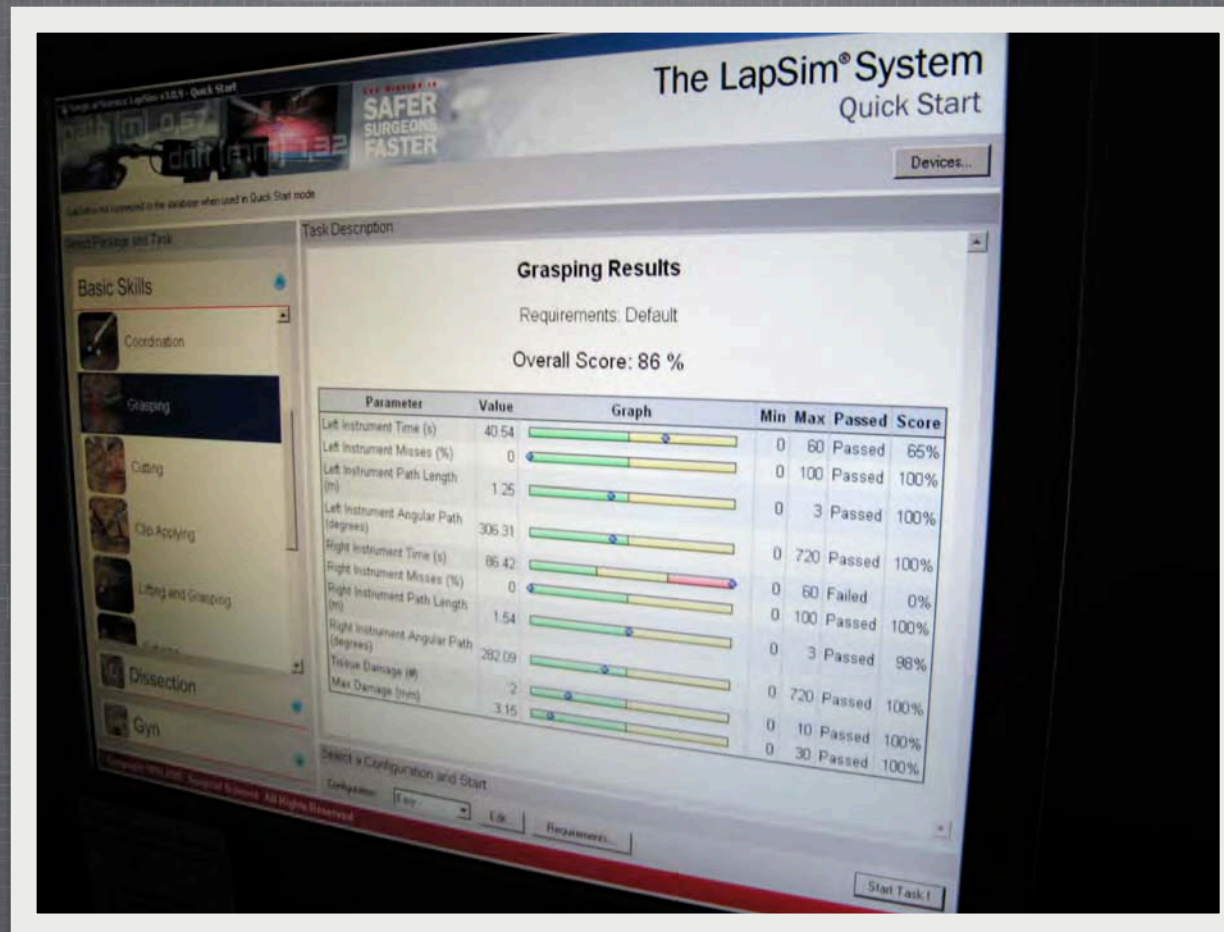
SD=Strongly Disagree, D=Disagree, N=Neutral, A=Agree, SA=Strongly Agree

# LAP SIM EXPERIMENT

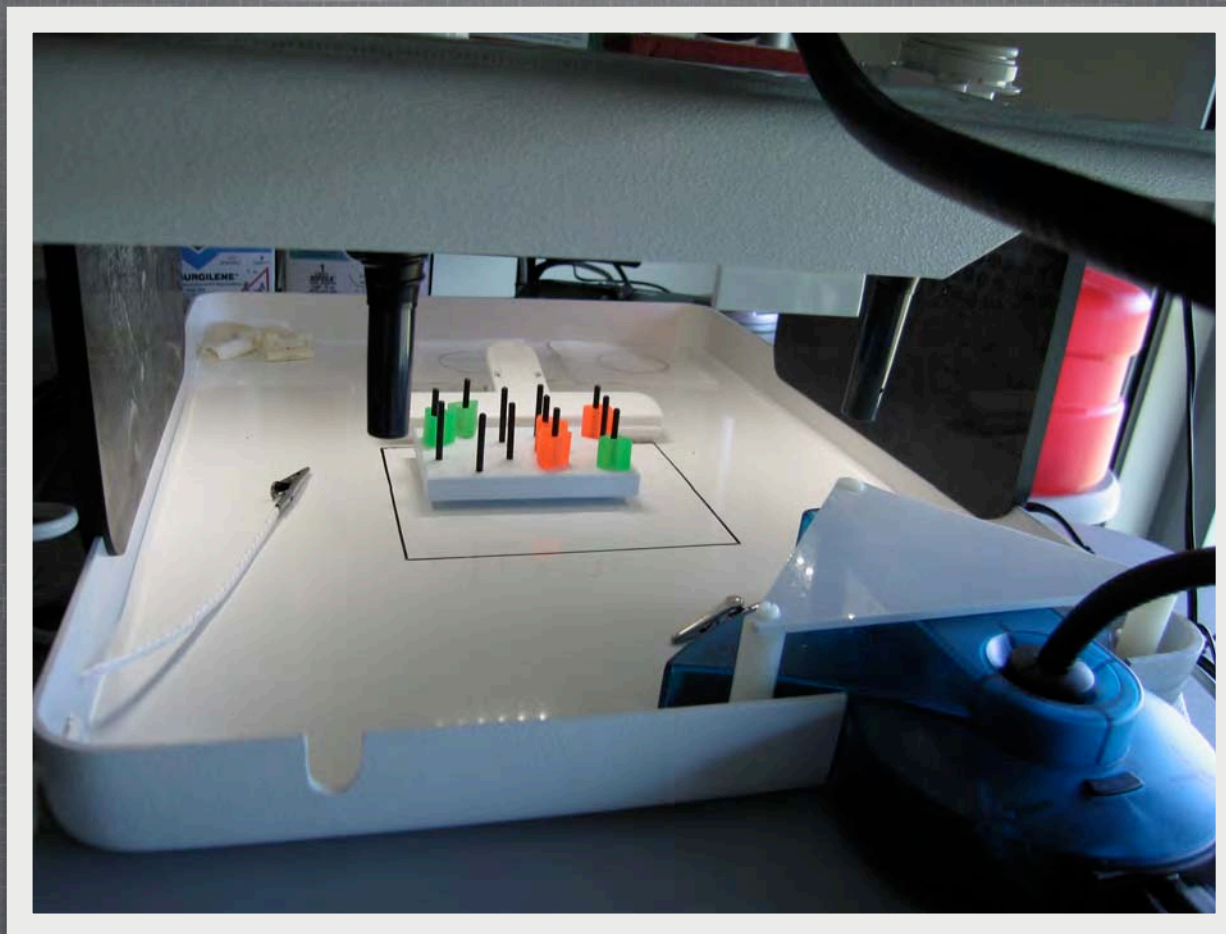
60 learners: randomly assigned to 3 groups  
Control Group, Lap Trainer group, SAGES group  
Gold Standard: LapSim performance



# Outcomes Measured on LapSim Trainer

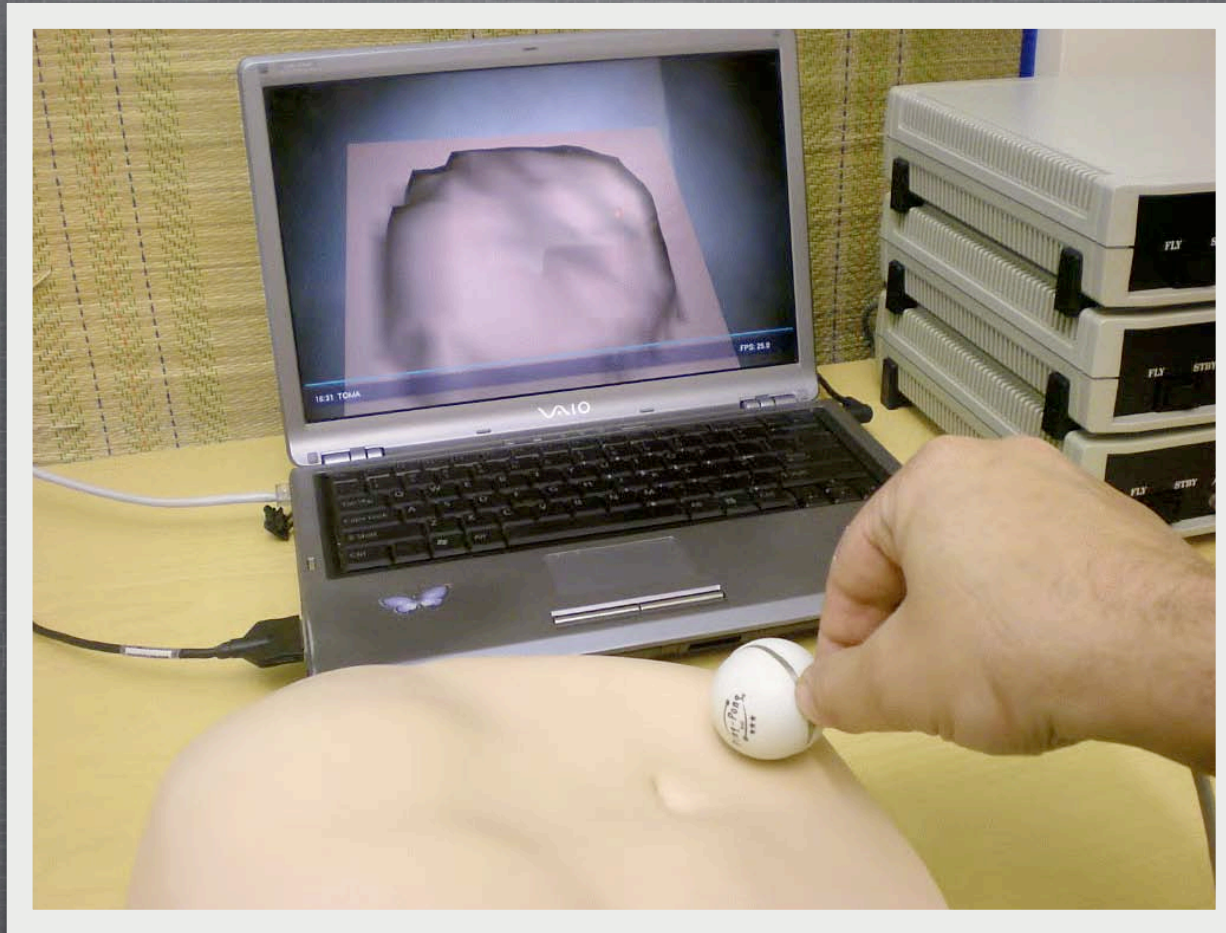


## SAGES trainer



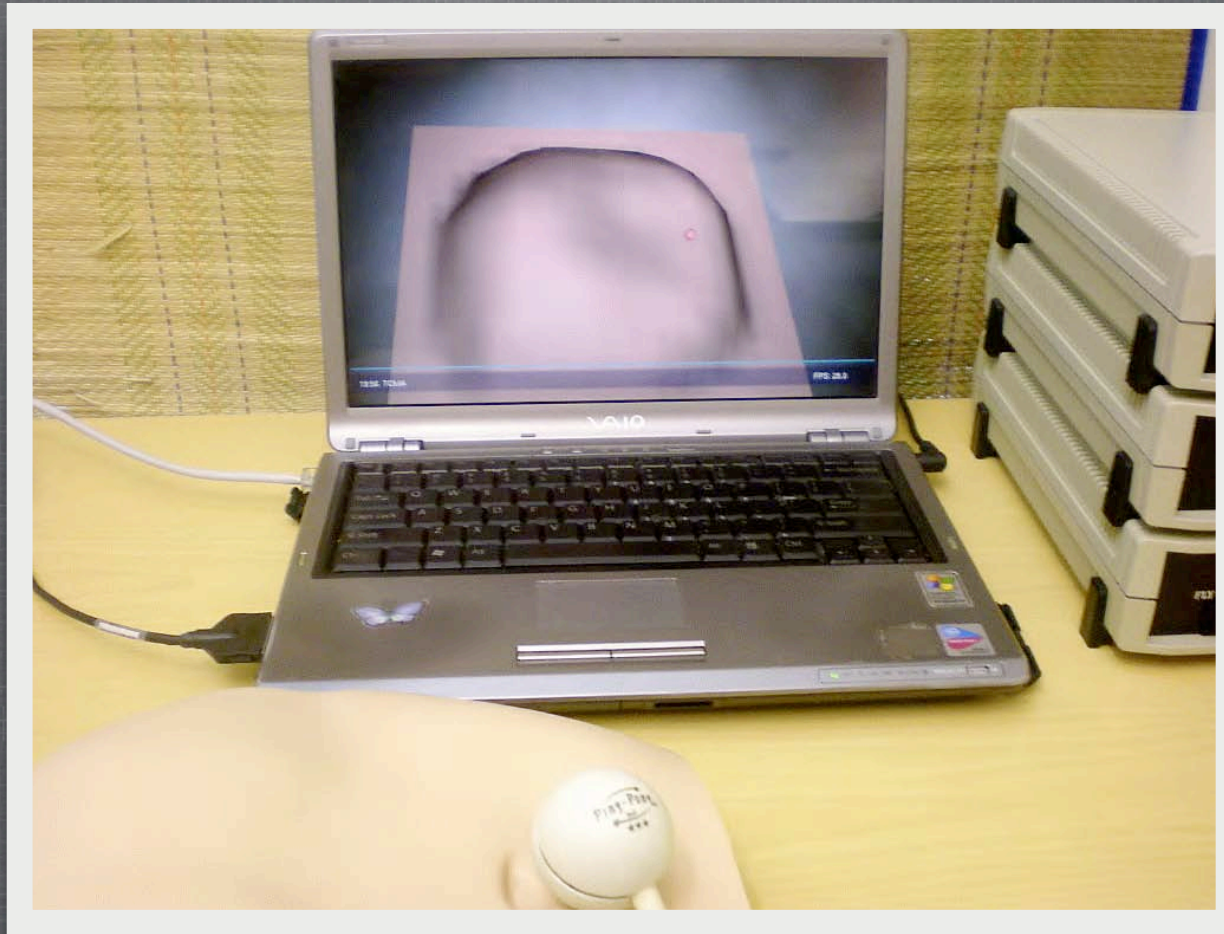
# TANGIBLE USER INTERFACE

## Fast Geometry Acquisition



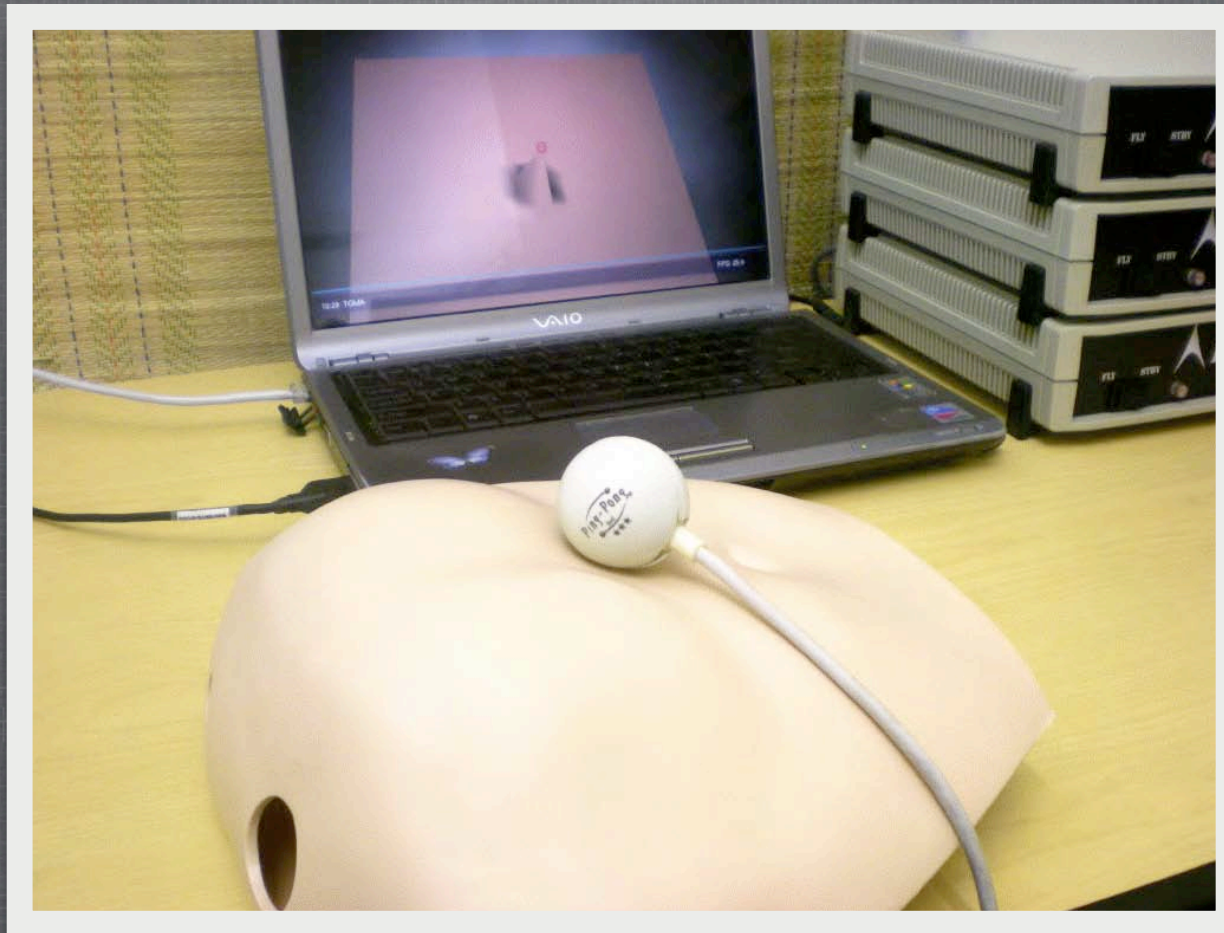
*User moves sensor over physical object to rapidly obtain crude 3D VR representation*

# Smoothing



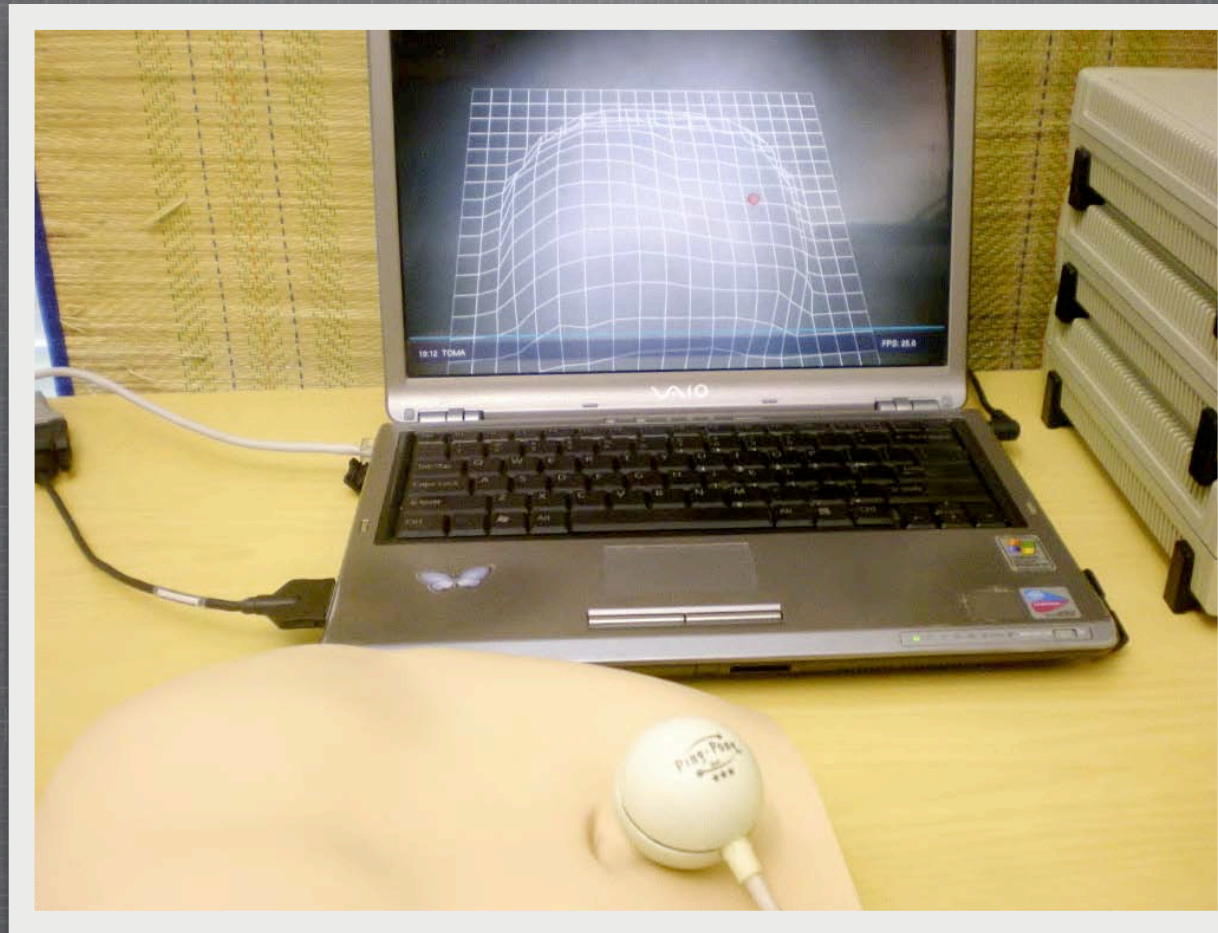
*Smoothing occurs in 3D VR image with more movement of the sensor over the physical object*

## VR acquisition of the convex landmark



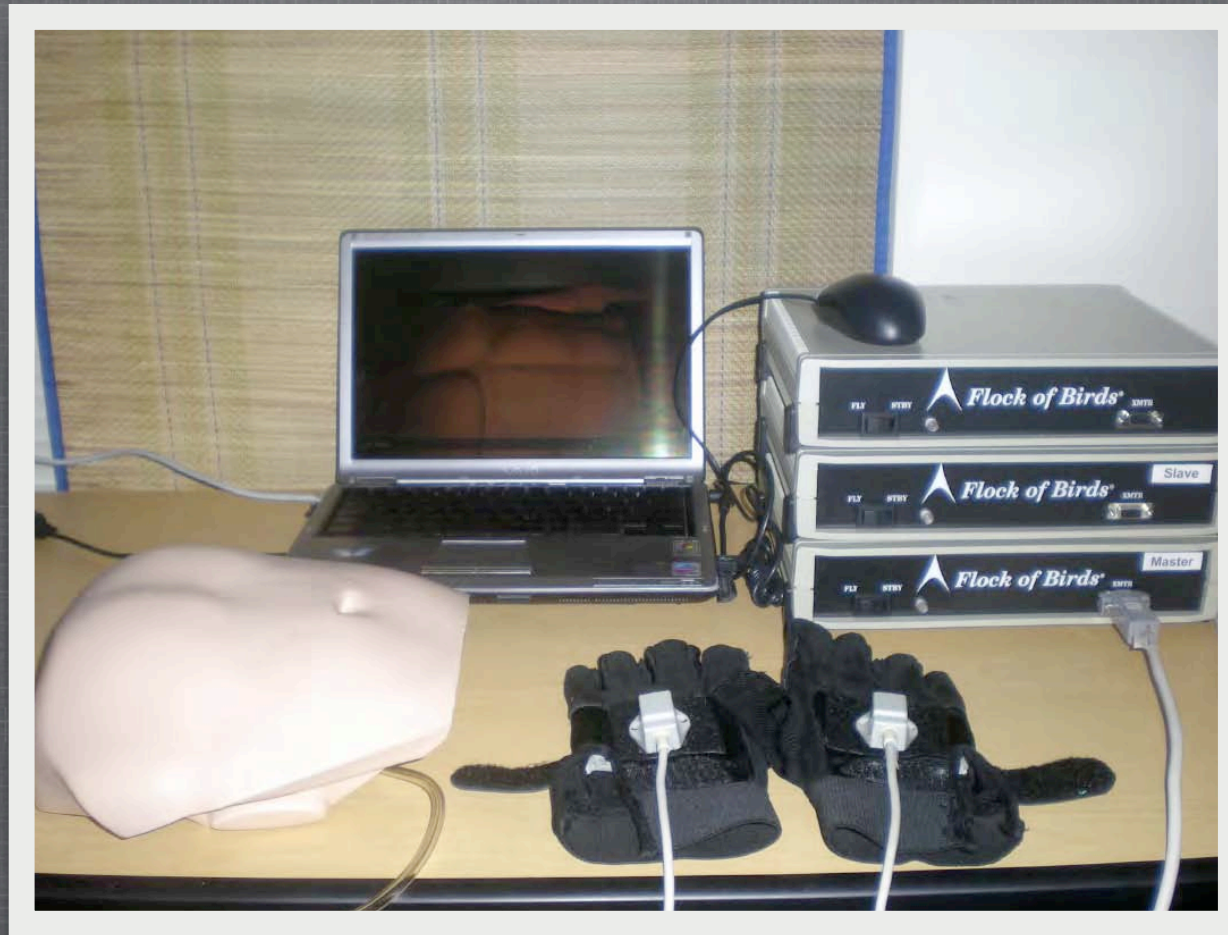
*Sensor is used to acquire and register a convex landmark: manikin umbilicus*

## 3D VR mesh representation of the physical object



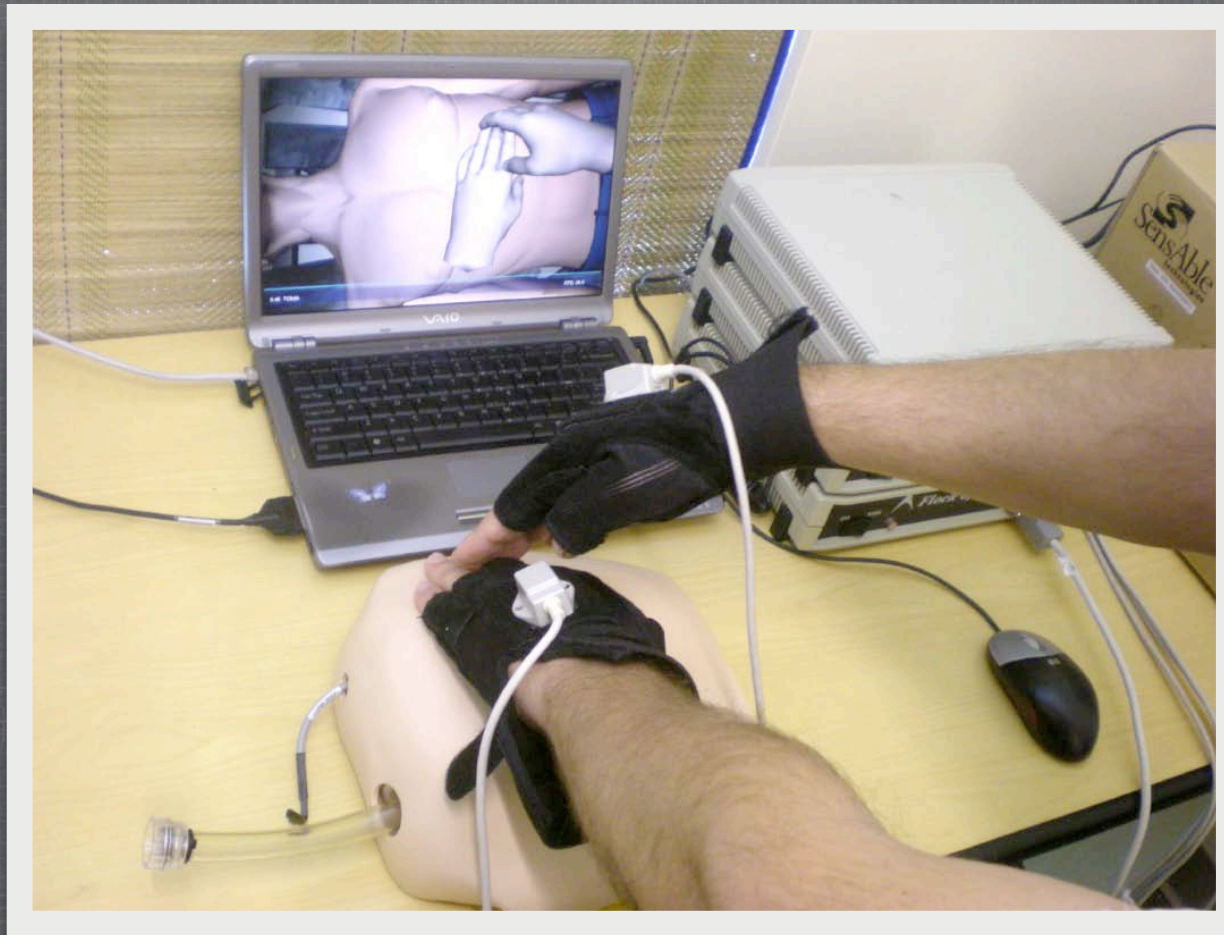
*3D VR mesh is deformed to take on shape of the physical object*

# Augmented Reality Interface using Motion Tracking and 3D VR



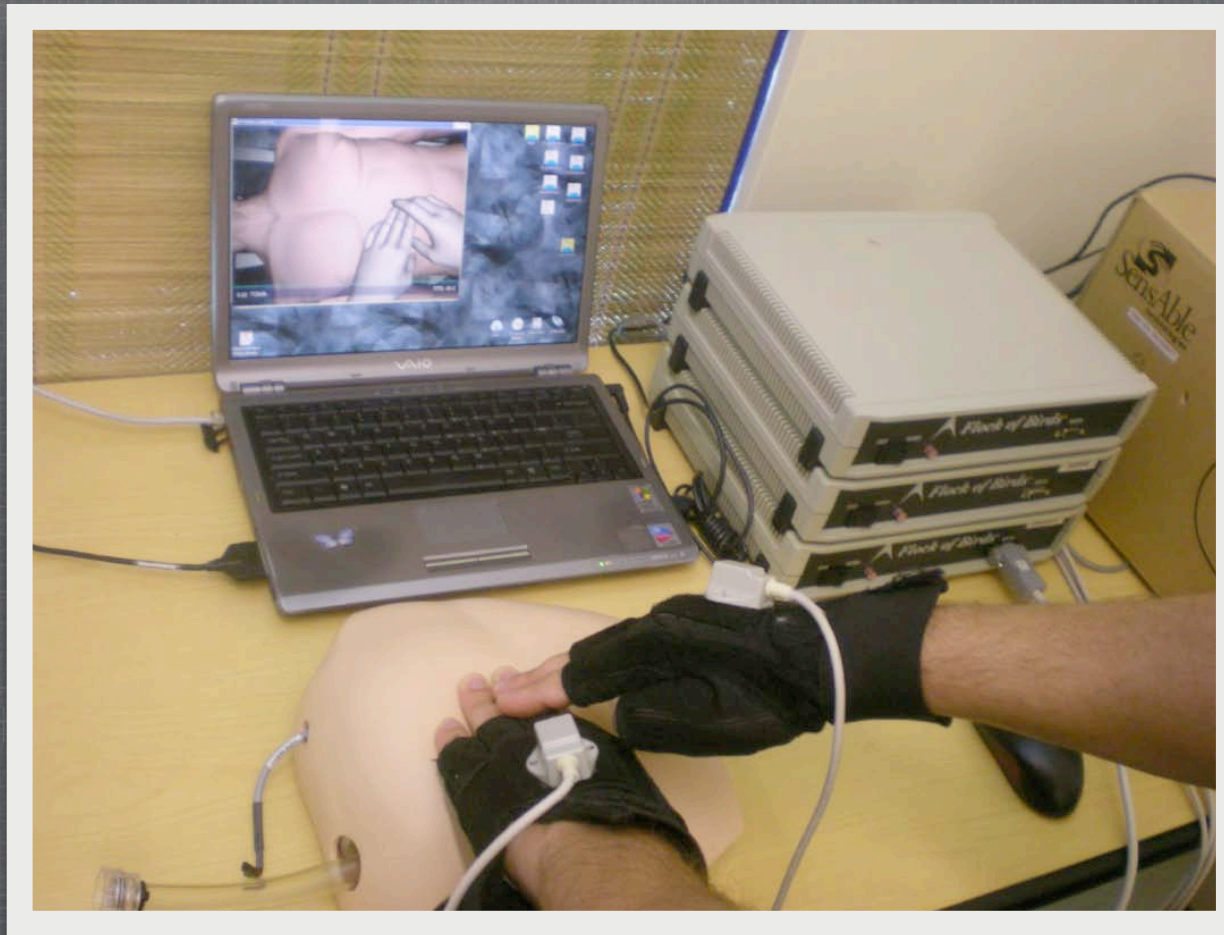
*Motion Tracking Sensors + Manikin + VR Software*

# Tapping on Physical Model is Mapped to VR Software



*Tapping represents a programmable Gesture-Command*

VR Command-Gestures elicit an output: “ouch”



*Sensor-Gloves are mapped to the Virtual Hands*